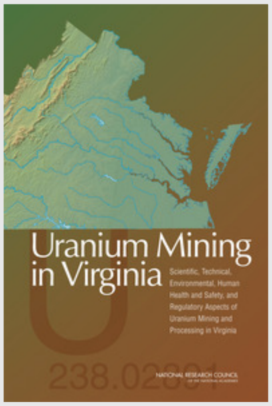

Uranium Mining in Virginia: Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in Virginia

DETAILS

359 pages | 6 x 9 | HARDBACK
ISBN 978-0-309-38777-4 | DOI 10.17226/13266

CONTRIBUTORS

Committee on Uranium Mining in Virginia; Committee on Earth Resources; Board on Earth Sciences and Resources; Division on Earth and Life Studies; National Research Council

Uranium Mining in Virginia

Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in Virginia

Committee on Uranium Mining in Virginia

Committee on Earth Resources

Board on Earth Sciences and Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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This study was supported by a grant from Virginia Polytechnic Institute and State University with funding provided by Virginia Uranium, Inc. The opinions, findings, and conclusions contained in this document are those of the authors and do not necessarily reflect the views of the study sponsors.

International Standard Book Number 13: 978-0-309-22087-3
International Standard Book Number 10: 0-309-22087-4

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

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Preface

The Commonwealth of Virginia first undertook the study of uranium mining and processing more than 25 years ago, after several potentially commercially viable deposits of uranium were discovered in the state. Since that time, issues surrounding uranium mining have raised substantial questions and have been extensively debated and discussed. In 2009, the National Research Council of the National Academies was asked to undertake this study and address a series of detailed questions about uranium mining, processing, and reclamation to assist decision making by the Commonwealth of Virginia.

In accepting its charge to address a highly emotive issue such as uranium mining and its related activities, the committee was mindful of its obligation to provide technical and scientific answers to the questions in its statement of task. In doing so, the committee benefited from briefings provided by international experts, including U.S. and international regulators, scientists, engineers, and others. Equally important, the committee benefited from the extensive testimony provided by the citizens of the Commonwealth of Virginia. We received many hours of public input, spread over all but one of our committee meetings, but particularly focused on the two evening "town hall" meetings that we held in Danville and Richmond, Virginia. Hundreds of members of local communities attended and spoke at these town hall sessions. On behalf of the committee, I wish to express our appreciation for the many specific comments and questions directed to the committee at these gatherings. We are hopeful that our report is reflective of what we learned, and that with this report we have managed to help inform the public discussion and debate on this important topic. Although we specifically do not make any recommendations concerning whether mining and processing of uranium should or should not be permitted in the Commonwealth

of Virginia, we believe that this report will provide a solid scientific basis to inform those who will make such decisions on behalf of Virginia citizens and their communities.

The need to prepare our report in time for the 2011-2012 legislative session in Virginia imposed a very tight time limit, as we sought to collectively understand the scientific, technical, and regulatory subtleties of issues usually outside our specific disciplines. As we started the committee process, we realized that it would not be possible, considering the breadth of the task statement and the time constraints, to prepare a scientifically and technically dense treatise. I thank the committee for rising to the challenge and preparing a report that we hope will be—as much as possible given the specialized nature of its content—accessible to legislators and the wider public who are interested in this topic. I would also like to thank the committee members for their thoughtful deliberations and willingness to consider alternative viewpoints and learn from, and share, expertise across disciplines.

Finally, the committee acknowledges the support provided by the National Research Council staff, who handled our numerous and sometimes challenging logistic and research demands. In particular, the committee would like to thank Deborah Glickson, Jason Ortego, and Solmaz Spence for contributing to the report writing and research efforts, and Courtney Gibbs and Penelope Gibbs for making sure that our meetings ran without a hitch. Stephanie Johnson added her scholarship and organizational skills and, by doing so, improved our work. Anthony de Souza provided the committee with his valuable perspective and experience.

Special thanks and praise go to two staff members who were instrumental to this report. Nicholas Rogers played a key role in almost all aspects of this project as a researcher and financial manager. And David Feary, our study director, kept the committee on track and moving in the right direction. The committee is indebted to him for his hard work and leadership.

Paul A. Locke, Chair
Committee on Uranium Mining in Virginia

Acknowledgments

This report was greatly enhanced by all those who made presentations to the committee at the public committee meetings, both the speakers specifically invited by the committee to make presentations as well as the numerous interested citizens who provided their perspectives and viewpoints. The presentations and discussions at these meetings provided invaluable input and context for the committee's deliberations. The provision of additional text and figures by William Lassetter, Theresa McClenaghan, Jim Neton, and Maria Angelica Zamora-Duran are also gratefully acknowledged.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Jan Beyea, Consulting in the Public Interest, Lambertville, New Jersey
Corale L. Brierley, Brierley Consulting, Highlands Ranch, Colorado
Philip Egidi, U.S. Environmental Protection Agency, Grand Junction, Colorado
Rodney C. Ewing, University of Michigan, Ann Arbor
John Greeves, JTG Consulting, Frederick, Maryland
Kelvin Gregory, Carnegie Mellon University, Pittsburgh, Pennsylvania
David C. Kocher, SENES Oak Ridge, Inc., Oak Ridge, Tennessee

Craig Little, Tow Lines Inc., Grand Junction, Colorado
Robert Pierson, Independent Consultant, Walkersville, West Virginia
Samuel B. Romberger, Colorado School of Mines, Golden
Jonathan M. Samet, University of Southern California, Los Angeles
William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, New York
Courtney Young, Montana Tech of the University of Montana, Butte

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Dianne R. Nielson, energy and environmental policy consultant, and Chris G. Whipple, ENVIRON International Corporation. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

In the 1970s and 1980s, exploration for uranium deposits in the Commonwealth of Virginia identified a number of areas containing potential ore deposits, and several large tracts of land in the Commonwealth were leased for exploration. A particularly rich deposit of uranium—the Coles Hill uranium deposit—was discovered in 1978 in Pittsylvania County, south central Virginia, and more detailed geological exploration of this deposit was undertaken in the 1980s. In 1982, the Commonwealth of Virginia enacted a statewide moratorium on uranium mining, although approval for restricted uranium exploration in the state was granted in 2007.

In 2009, the National Research Council was commissioned to prepare a report describing the scientific, technical, environmental, human health and safety, and regulatory aspects of uranium mining and processing as they relate to the Commonwealth of Virginia, with the ultimate objective of providing independent, expert advice to help inform decisions about uranium mining and processing in Virginia. The impetus for this study came from the Virginia legislature, in the form of a request from the Virginia Coal and Energy Commission. Additional letters supporting this request were received from U.S. Senators Mark Warner and Jim Webb and from Governor Kaine. The study was funded under a contract with the Virginia Center for Coal and Energy Research at Virginia Polytechnic Institute and State University (Virginia Tech); funding for the study was provided to Virginia Tech by Virginia Uranium, Inc.

The formal task statement for the study committee was wide-ranging, encompassing the physical and social context in which uranium mining and processing might occur; the occurrences and exploration status of uranium in Virginia and the global and national uranium markets; the primary technical options and best

practices for uranium mining, processing, and reclamation that might be applicable within the Commonwealth of Virginia; and the potential impact of uranium mining, processing, and reclamation operations on occupational and public health, safety, and the environment. A review of the state and federal regulatory framework for uranium mining, processing, and reclamation was also identified as part of the committee's charge. The task statement required scientific and technical analysis, and although the social context is included as a required component, consideration of the potential socioeconomic impacts of uranium mining and processing was outside the committee's purview. The task statement for the committee specifically noted that the study should not make recommendations about whether or not uranium mining should be permitted, and would not include site-specific assessments.

The committee met seven times over 11 months, and all but one of the meetings included time set aside for public comment. This included two evening sessions organized as "town hall"-style meetings, to receive community input and commentary. In addition, the committee traveled to northeastern Saskatchewan, Canada, for site visits to two uranium mines and associated processing facilities. This challenging schedule was designed to allow the committee to receive briefings regarding the scientific and technical aspects of its charge; to receive input from individuals and community organizations; to deliberate on its findings; and to write its report. The committee's deliberations resulted in a series of findings and key concepts covering the broad range of its task statement, together with some overarching as well as specific best practices related to uranium mining, processing, reclamation, and long-term stewardship. These findings and key concepts are summarized as bullet points under a series of specific topic headings below. Note that the description of potential impacts of uranium mining, processing, and reclamation operations on occupational and public health, safety, and the environment are presented separately from the section on the range of best practices that could be applied to mitigate some of these adverse impacts.

VIRGINIA PHYSICAL AND SOCIAL CONTEXT

- Virginia has a diverse natural and cultural heritage, and a detailed assessment of both the potential site and its surrounding area (including natural, historical, and social characteristics) would be needed if uranium mining and processing were to be undertaken. Virginia's natural resources include a wide range of plants, animals, and ecosystems, a large number of which are currently under significant stress.
- The demographic makeup of the state varies greatly, both among and within its physiographic provinces.
- Virginia is subject to extreme natural events, including relatively large precipitation events and earthquakes. Although very difficult to accurately forecast, the risks and hazards associated with extreme natural events would need to

be taken into account when evaluating any particular site's suitability for uranium mining and processing operations.

URANIUM OCCURRENCES, RESOURCES, AND MARKETS

- Of the localities in Virginia where existing exploration data indicate that there are significant uranium occurrences, predominantly in the Blue Ridge and Piedmont geological terrains, only the deposits at Coles Hill in Pittsylvania County appear to be potentially economically viable at present.
- Because of their geological characteristics, none of the known uranium occurrences in Virginia would be suitable for the in situ leaching/in situ recovery (ISL/ISR) uranium mining/processing technique.
- In 2008, uranium was produced in 20 countries; however, more than 92 percent of the world's uranium production came from only eight countries (Kazakhstan, Canada, Australia, Namibia, Niger, Russia, Uzbekistan, and the United States).
- In general, uranium price trends since the early 1980s have closely tracked oil price trends. The Chernobyl (Ukraine) nuclear accident in 1986 did not have a significant impact on uranium prices, and it is too early to know the long-term uranium demand and price effects of the Fukushima (Japan) accident.
- Existing known identified resources of uranium, based on present-day reactor technologies and assuming that the resources are developed, are sufficient to last for more than 50 years at today's rate of usage.

MINING, PROCESSING, AND RECLAMATION

- The choice of mining methods and processing parameters for uranium recovery depends on multiple factors that are primarily associated with the geological and geotechnical characteristics of a uranium deposit—its mineralogy and rock type, as well as a range of other factors. Additional factors that require consideration are the location and depth of the deposit, whether the location is in a positive or negative water balance situation, as well as a range of environmental and socioeconomic factors. Consequently, a final design would require extensive site-specific analysis, and accordingly it is not possible at this stage to predict what specific type of uranium mining or processing might apply to ore deposits in Virginia.[1]
- Uranium recovery from ores is primarily a hydrometallurgical process using chemical processes with industrial chemicals, with a lesser dependence on physical processes such as crushing and grinding.
- Mine design—whether open pit or underground—requires detailed engineering planning that would include pit and rock stability considerations, as well

[1]The report notes that in situ leaching/in situ recovery (ISL/ISR) mining methods are unlikely to be applicable in Virginia because of the geological characteristics of known uranium occurrences.

as ventilation design to account for the presence of radon and other respiratory hazards.

- With the ore grades expected in Virginia, many of the technical aspects of mining for uranium would be essentially the same as those applying to other hard-rock mining operations. However, uranium mining and processing add another dimension of risk because of the potential for exposure to elevated concentrations of radionuclides.
- A complete life-cycle analysis is an essential component of planning for the exploitation of a uranium deposit—from exploration, through engineering and design, to startup, operations, reclamation, and finally to decommissioning leading to final closure and postclosure monitoring.

POTENTIAL HEALTH EFFECTS

- Uranium mining and processing are associated with a wide range of potential adverse human health risks. Some of these risks arise out of aspects of uranium mining and processing specific to that enterprise, whereas other risks apply to the mining sector generally, and still others are linked more broadly to large-scale industrial or construction activities. These health risks typically are most relevant to individuals occupationally exposed in this industry, but certain exposures and their associated risks can extend via environmental pathways to the general population.
- Protracted exposure to radon decay products generally represents the greatest radiation-related health risk from uranium-related mining and processing operations. Radon's alpha-emitting radioactive decay products are strongly and causally linked to lung cancer in humans. Indeed, the populations in which this has been most clearly established are uranium miners that were occupationally exposed to radon.
- In 1987, the National Institute for Occupational Safety and Health (NIOSH) recognized that current occupational standards for radon exposure in the United States do not provide adequate protection for workers at risk of lung cancer from protracted radon decay exposure, recommending that the occupational exposure limit for radon decay products should be reduced substantially. To date, this recommendation by NIOSH has not been incorporated into an enforceable standard by the U.S. Department of Labor's Mine Safety and Health Administration or the Occupational Safety and Health Administration.
- Radon and its alpha-emitting radioactive decay products are generally the most important, but are not the sole radionuclides of health concern associated with uranium mining and processing. Workers are also at risk from exposure to other radionuclides, including uranium itself, which undergo radioactive decay by alpha, beta, or gamma emission. In particular, radium-226 and its decay products (e.g., bismuth-214 and lead-214) present alpha and gamma radiation hazards to uranium miners and processors.

- Radiation exposures to the general population resulting from off-site releases of radionuclides (e.g., airborne radon decay products, airborne thorium-230 (^{230}Th) or radium-226 (^{226}Ra) particles, ^{226}Ra in water supplies) present some risk. The potential for adverse health effects increases if there are uncontrolled releases as a result of extreme events (e.g., floods, fire, earthquakes) or human error. The potential for adverse health effects related to releases of radionuclides is directly related to the population density near the mine or processing facility.
- Internal exposure to radioactive materials during uranium mining and processing can take place through inhalation, ingestion, or through a cut in the skin. External radiation exposure (e.g., exposure to beta, gamma, and to a lesser extent, alpha radiation) can also present a health risk.
- Because ^{230}Th and ^{226}Ra are present in mine tailings, these radionuclides and their decay products can—if not controlled adequately—contaminate the local environment under certain conditions, in particular by seeping into water sources and thereby increasing radionuclide concentrations. This, in turn, can lead to a risk of cancer from drinking water (e.g., cancer of the bone) that is higher than the risk of cancer that would have existed had there been no radionuclide release from tailings.
- A large proportion of the epidemiological studies performed in the United States, exploring adverse health effects from potential off-site radionuclide releases from uranium mining and processing facilities, have lacked the ability to evaluate causal relationships (e.g., to test study hypotheses) because of their ecological study design.
- The decay products of uranium (e.g., ^{230}Th, ^{226}Ra) provide a constant source of radiation in uranium tailings for thousands of years, substantially outlasting the current U.S. regulations for oversight of processing facility tailings.
- Radionuclides are not the only uranium mining- and processing-associated occupational exposures with potential adverse human health effects; two other notable inhalation risks are posed by silica dust and diesel exhaust. Neither of these is specific to uranium mining, but both have been prevalent historically in the uranium mining and processing industry. Of particular importance is the body of evidence from occupational studies showing that both silica and diesel exhaust exposure increase the risk of lung cancer, the main risk also associated with radon decay product exposure. To the extent that cigarette smoking poses further risk in absolute terms, there is potential for increased disease, including combined effects that are more than just additive.
- Although uranium mining-specific injury data for the United States were not available for review, work-related physical trauma risk (including electrical injury) is particularly high in the mining sector overall and this could be anticipated to also apply to uranium mining. In addition, hearing loss has been a major problem in the mining sector generally, and based on limited data from overseas studies, may also be a problem for uranium mining.

- A number of other exposures associated with uranium mining or processing, including waste management, also could carry the potential for adverse human health effects, although in many cases the detailed studies that might better elucidate such risks are not available.
- Assessing the potential risks of multiple combined exposures from uranium mining and processing activities is not possible in practical terms, even though the example of multiple potential lung carcinogen exposures in uranium mining and processing underscores that this is more than a theoretical concern.

POTENTIAL ENVIRONMENTAL EFFECTS

- Uranium mining, processing, and reclamation in Virginia have the potential to affect surface water quality and quantity, groundwater quality and quantity, soils, air quality, and biota. The impacts of these activities in Virginia would depend on site-specific conditions, the rigor of the monitoring program established to provide early warning of contaminant migration, and the efforts to mitigate and control potential impacts. If uranium mining, processing, and reclamation are designed, constructed, operated, and monitored according to modern international best practices, near- to moderate-term environmental effects specific to uranium mining and processing should be substantially reduced.
- Tailings disposal sites represent potential sources of contamination for thousands of years, and the long-term risks remain poorly defined. Although significant improvements have been made in recent years to tailings management engineering and designs to isolate mine waste from the environment, limited data exist to confirm the long-term effectiveness of uranium tailings management facilities that have been designed and constructed according to modern best practices.
- Significant potential environmental risks are associated with extreme natural events and failures in management practices. Extreme natural events (e.g., hurricanes, earthquakes, intense rainfall events, drought) have the potential to lead to the release of contaminants if facilities are not designed and constructed to withstand such an event, or fail to perform as designed.
- Models and comprehensive site characterization are important for estimating the potential environmental effects associated with a specific uranium mine and processing facility. A thorough site characterization, supplemented by air quality and hydrological modeling, is essential for estimating the potential environmental impacts of uranium mining and processing under site-specific conditions and mitigation practices.

REGULATION AND OVERSIGHT

- The activities involved in uranium mining, processing, reclamation, and long-term stewardship are subject to a variety of federal and state laws that are the responsibility of numerous federal and state agencies.

- Because the Commonwealth of Virginia enacted a moratorium on uranium mining in 1982, the state has essentially no experience regulating uranium mining and there is no existing regulatory infrastructure specifically for uranium mining. The state does have programs that regulate hard-rock mining and coal mining.
- There is no federal law that specifically applies to uranium mining on non-federally owned lands; state laws and regulations have jurisdiction over these mining activities. Federal and state worker protection laws, and federal and state environmental laws, variously apply to occupational safety and health, and air, water, and land pollution resulting from mining activities.
- At present, there are gaps in legal and regulatory coverage for activities involved in uranium mining, processing, reclamation, and long-term stewardship. Some of these gaps have resulted from the moratorium on uranium mining that Virginia has in place; others are gaps in current laws or regulations, or in the way that they are applied. Although there are several options for addressing these gaps, the committee notes that Canada and the state of Colorado have enacted laws and promulgated regulations based on best practices that require modern mining and processing methods, and empower regulatory agencies with strong information-gathering, enforcement, and inspection authorities. In addition, best practice would be for state agencies, with public stakeholder involvement, to encourage the owner/operator of a facility to go beyond the regulations to adopt international industry standards if they are more rigorous than the existing regulations.
- The U.S. federal government has only limited recent experience regulating conventional[2] uranium processing and reclamation of uranium mining and processing facilities. Because almost all uranium mining and processing to date has taken place in parts of the United States that have a negative water balance, federal agencies have limited experience applying laws and regulations in positive water balance situations. The U.S. federal government has considerable experience attempting to remediate contamination due to past, inappropriate practices at closed or abandoned sites.
- Under the current regulatory structure, opportunities for meaningful public involvement are fragmented and limited.

BEST PRACTICES

At a high level, there are three overarching best-practice concepts, consistent with practices that are recognized and applied by the international uranium mining and processing community:

- Development of a uranium mining and processing facility has planning, construction, production, closure, and long-term stewardship phases, and best

[2]Conventional mining and processing includes surface or open-pit mining, or some combination of the two, and their associated processing plants, but excludes ISL/ISR uranium recovery.

practice requires a complete life-cycle approach during the project planning phase. Planning should take into account all aspects of the process—including the eventual closure, site remediation and reclamation, and return of the affected area to as close to natural condition as possible—prior to initiation of a project. Good operating practice is for site and waste remediation to be carried out on a continual basis during ore recovery, thereby reducing the time and costs for final decommissioning, remediation, and reclamation. Regular and structured risk analyses, hazard analyses, and operations analyses should take place within a structured change management system, and the results of all such assessments should be openly available and communicated to the public.

- Development of a mining and/or processing project should use the expertise and experience of professionals familiar with internationally accepted best practices, to form an integrated and cross-disciplinary collaboration that encompasses all components of the project, including legal, environmental, health, monitoring, safety, and engineering elements.
- Meaningful and timely public participation should occur throughout the life cycle of a project, beginning at the earliest stages of project planning. This requires creating an environment in which the public is both informed about, and can comment upon, any decisions made that could affect their community. Notice should be given to interested parties in a timely manner so that their participation in the regulatory decision-making process can be maximized. All stages of permitting should be transparent, with independent advisory reviews. One important contribution to transparency is the development of a comprehensive Environmental Impact Statement for any proposed uranium mining and processing facility.

At a more specific level, this report contains best-practice guidelines that encompass a diverse range of issues that would need to be addressed during planning for any uranium mining and processing project:

- A number of detailed specific best-practice documents (e.g., guidelines produced by the World Nuclear Association, International Atomic Energy Agency, and International Radiation Protection Association) exist that describe accepted international best practices for uranium mining and processing projects. Although these documents are by their nature generic, they provide a basis from which specific requirements for any uranium mining and processing projects in Virginia could be developed.
- Some of the worker and public health risks could be mitigated or better controlled if uranium mining, processing, and reclamation are all conducted according to best practices, which at a minimum for workers would include the use of personal dosimetry—including for radon decay products—and a national radiation dose registry for radiation- and radon-related hazards. NIOSH-recommended exposure limits for radon, diesel gas and particulates, occupational noise, and silica hazards represent minimal best practices for worker protection.

- A well-designed and executed monitoring plan, available to the public, is essential for gauging performance, determining and demonstrating compliance, triggering corrective actions, fostering transparency, and enhancing site-specific understanding. The monitoring strategy, encompassing baseline monitoring, operational monitoring, and decommissioning and postclosure monitoring, should be subject to annual updates and independent reviews to incorporate new knowledge or enhanced understanding gained from analysis of the monitoring data.
- Because the impacts of uranium mining and processing projects are, by their nature, localized, modern best practice is for project implementation and operations, whenever possible, to provide benefits and opportunities to the local region and local communities.
- Regulatory programs are inherently reactive, and as a result the standards contained in regulatory programs represent only a starting point for establishing a protective and proactive program for protecting worker and public health, environmental resources, and ecosystems. The concept of ALARA[3] (as low as is reasonably achievable) is one way of enhancing regulatory standards.

CONCLUSION

The committee's charge was to provide information and advice to the Virginia legislature as it weighs the factors involved in deciding whether to allow uranium mining. This report describes a range of potential issues that could arise if the moratorium on uranium mining were to be lifted, as well as providing information about best practices—applicable over the full uranium extraction life cycle—that are available to mitigate these potential issues.

If the Commonwealth of Virginia rescinds the existing moratorium on uranium mining, there are steep hurdles to be surmounted before mining and/or processing could be established within a regulatory environment that is appropriately protective of the health and safety of workers, the public, and the environment. There is only limited experience with modern underground and open-pit uranium mining and processing practices in the wider United States, and no such experience in Virginia. At the same time, there exist internationally accepted best practices, founded on principles of openness, transparency, and public involvement in oversight and decision making, that could provide a starting point for the Commonwealth of Virginia were it to decide that the moratorium should be lifted. After extensive scientific and technical briefings, substantial public input,

[3]ALARA (an acronym for "as low as is reasonably achievable") is defined as "means making every reasonable effort to maintain exposures to radiation as far below the dose limits . . . as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest" (10 CFR § 20.1003).

reviewing numerous documents, and extensive deliberations, the committee is convinced that the adoption and rigorous implementation of such practices would be necessary if uranium mining, processing, and reclamation were to be undertaken in the Commonwealth of Virginia.

Nontechnical Summary

In recent years, there has been renewed interest in mining uranium in the Commonwealth of Virginia. However, before any mining could begin, Virginia's General Assembly would have to rescind a statewide moratorium on uranium mining that has been in effect since 1982. The National Research Council was commissioned to provide an independent review of the scientific, environmental, human health and safety, and regulatory aspects of uranium mining, processing, and reclamation in Virginia to help inform the public discussion about uranium mining and to assist Virginia's lawmakers in their deliberations.

Beneath Virginia's rolling hills, there are occurrences of uranium (Box NS.1), a naturally occurring radioactive element that can be used to make fuel for nuclear power plants. In the 1970s and early 1980s, work to explore these resources led to the discovery of a large uranium deposit at Coles Hill, located in Pittsylvania County in southern Virginia. However, in 1982 the Commonwealth of Virginia enacted a moratorium on uranium mining, and interest in further exploring the Coles Hill deposit waned.

In 2007, two families living in the vicinity of Coles Hill formed a company called Virginia Uranium, Inc. to begin exploring the uranium deposit once again. Since then, there have been calls for the Virginia legislature to lift the uranium mining moratorium statewide.

To help inform deliberations on the possibility of future uranium mining in Virginia, the Virginia Coal and Energy Commission requested that the National Research Council convene an independent committee of experts to write a report that described the scientific, environmental, human health and safety, and regula-

BOX NS.1. What Is Uranium?

Uranium is a radioactive element found at low concentrations in virtually all rock, soil, and seawater. Significant concentrations of uranium can occur in phosphate rock deposits and minerals such as pitchblende and uraninite.

FIGURE NS.1 Photograph shows sample of the uranium-containing mineral uraninite. SOURCE. Photograph by Andrew Silver, Brigham Young University. Image courtesy of the U.S. Geological Survey.

tory aspects of mining and processing Virginia's uranium resources. Additional letters supporting this request were received from U.S. Senators Mark Warner and Jim Webb and from Governor Kaine. The National Research Council study was funded under a contract with the Virginia Center for Coal and Energy Research at Virginia Polytechnic Institute and State University (Virginia Tech). Funding for the study was provided to Virginia Tech by Virginia Uranium, Inc. The expert members of the National Research Council committee served as volunteers, without payment for their time, for the 18-month period during which the study was conducted.

The resulting report is intended to provide an independent scientific and technical review to inform the public and the Virginia legislature. The report does not focus on the Coles Hill deposit, but instead considers uranium mining, processing, and reclamation in the Commonwealth of Virginia as a whole. The committee was not asked to consider the benefits of uranium mining either to the nation or to the local economy, nor was it asked to assess the relative risks of uranium mining compared with the mining and processing of other energy sources, for example coal. The committee was also not asked to make any recommendations about whether or not uranium mining should be permitted in the Commonwealth of Virginia.

WHAT IS URANIUM USED FOR?

The main commercial use of uranium is to make fuel for nuclear power reactors, which provide 20 percent of electricity generation in the United States. As with power stations fueled by fossil fuels such as coal or natural gas, nuclear power stations heat water to produce steam that in turn drives turbines to generate electricity. In a nuclear power station, the nuclear fission of uranium atoms replaces the burning of coal or gas as the energy source.

PREDICTING FUTURE DEMAND FOR URANIUM

The market for uranium is driven by the electric power industry's need for nuclear power. As of November 2011, the United States has 104 nuclear reactors in operation, and in 2011 these reactors required 20,256 short tons (18,376 metric tonnes, as shown in Figure NS.2) of concentrated uranium. Projections for future energy use by the Nuclear Energy Agency and the International Atomic Energy Agency show that by 2035, reactors in the United States are expected to require between 12,000 and 25,000 tons of uranium per year. In 2010, the United States imported more than 90 percent of the uranium that it needed to fuel its nuclear power stations.

Understanding future uranium demand is difficult because it is hard to predict when aging reactors will be retired, and when new reactors will be constructed. Also, unanticipated events at nuclear power plants, such as the Chernobyl or Fukushima accidents, could affect how people and governments plan for and utilize nuclear power. This affects demand for nuclear energy and, therefore, uranium.

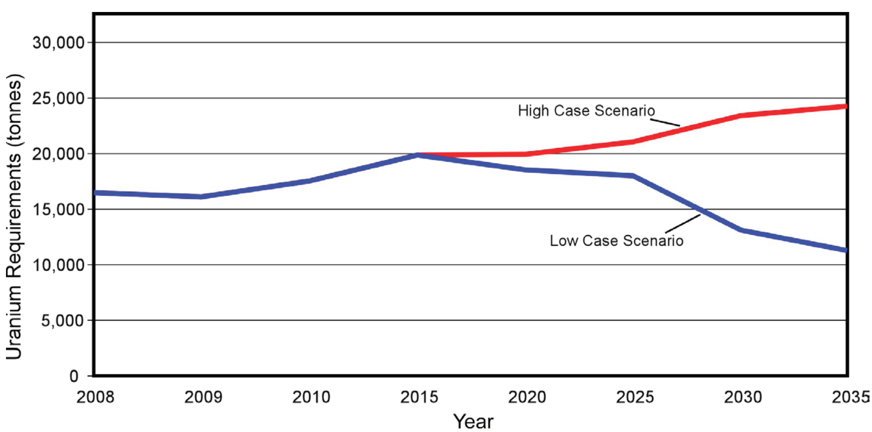

FIGURE NS.2 Projections for uranium requirements to fuel nuclear reactors in the United States through 2035. SOURCE: Compiled from data in NEA/IAEA (2010).

WHERE DOES THE SUPPLY OF URANIUM COME FROM?

Uranium comes from mining uranium ore deposits, from existing stockpiles held by government and commercial entities, and from recycling uranium from sources such as spent nuclear fuel from nuclear power plants and nuclear warheads. In 2009, world uranium mining fulfilled 74 percent of world reactor requirements, and the remaining 26 percent came from secondary sources such as stockpiles and decommissioned warheads.

Uranium was produced in 20 countries in 2010, but eight countries accounted for more than 92 percent of the world's uranium production (see Figure NS.3). The United States accounted for 3 percent of global uranium production. Overall, world uranium primary production increased steadily between 2000 and 2009, with Kazakhstan, Namibia, Australia, Russia, and Brazil showing marked increases between 2006 and 2009 to offset decreased production in Canada, Niger, the United States, and the Czech Republic. In the United States, production increased markedly from 2003 to 2006, but then slowed due to operational challenges and lower uranium prices.

Geological exploration has identified more than 55 occurrences of uranium in Virginia (see Figure NS.4). These are located primarily in the Piedmont and Blue Ridge regions. For a uranium occurrence to be considered a commercially

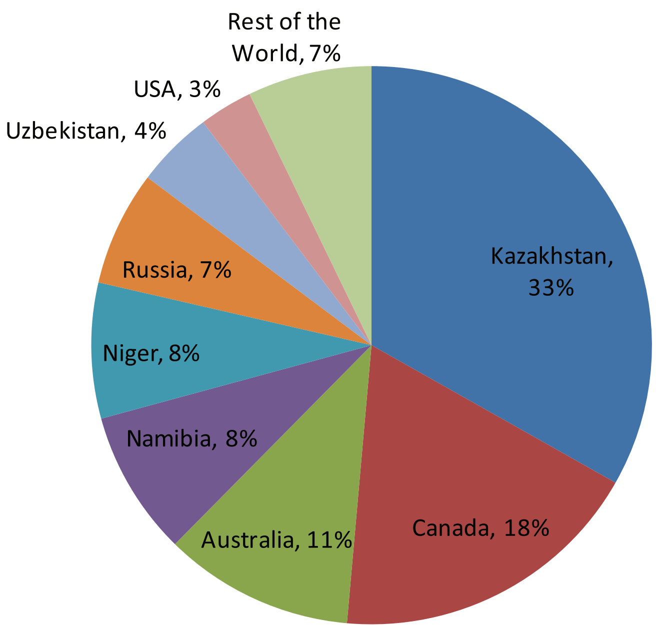

FIGURE NS.3 World uranium production in 2010. Eight countries accounted for more than 92 percent of global uranium production. SOURCE: WNA (2011b).

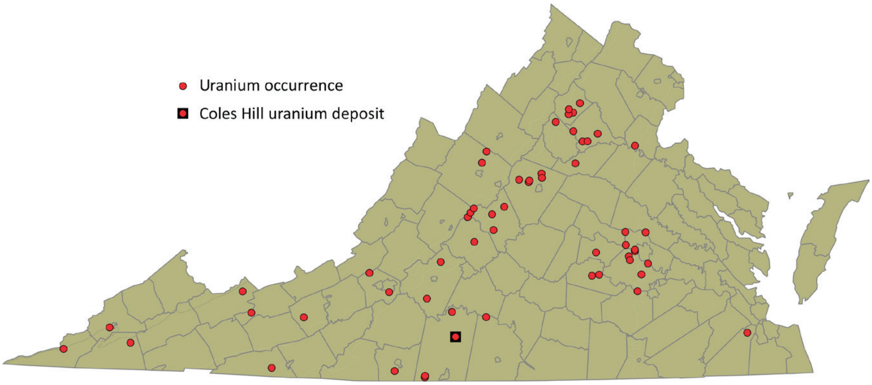

FIGURE NS.4 Uranium occurrences (not necessarily uranium ore deposits) identified in Virginia so far. The red square in the lower, central portion of the map indicates the Coles Hill deposit. SOURCE: Adapted from Lassetter (2010).

exploitable source of uranium ore, it must be of sufficient size, appropriate grade (have enough uranium compared with the other rock in the deposit), and be amenable to mining and processing. Of the sites explored in Virginia so far, only the deposit at Coles Hill is large enough, and of a high enough grade, to be potentially economically viable.

LIFE CYCLE OF A URANIUM MINE AND PROCESSING FACILITY

The process of taking uranium ore out of the ground and transforming it into yellowcake (Box NS.2), as well as the cleanup and reclamation of the site during mining and processing operations and after operations have ceased, includes several components:

- ***Mining:*** There are three types of mining that could be used to extract uranium ore from the ground. These are open-pit mining, underground mining, and in situ ("in place") leaching/in situ recovery (ISL/ISR—the process of recovering the uranium from the ground by dissolving the uranium minerals in liquid underground and then pumping that liquid to the surface, where the uranium is then taken out of the solution). In effect, ISL/ISR combines mining and some of the processing steps. The choice of mining method depends on many factors, including the quality and quantity of the ore, the shape and depth of the ore deposit, the type of rock surrounding the ore deposit, and a wide range of site-specific environmental conditions. Because of the geology in the Commonwealth of Virginia, it is very unlikely that ISL/ISR can be used to extract uranium anywhere in the state. Accordingly, the report focuses on conventional mining—open-pit

BOX NS.2. What Is Yellowcake?

Yellowcake is the concentrated form of uranium oxide made by processing uranium ore. Yellowcake is refined, enriched, and undergoes chemical conversion in specialized uranium enrichment facilities to produce fuel for nuclear power plants.

mining and underground mining, and the processing of the ore that comes from conventional mines.

- ***Processing:*** After the ore from conventional mines is removed from the ground, it must be processed to remove impurities and produce yellowcake. This involves both physical processes (such as crushing and/or grinding) and chemical processes (i.e., dissolving uranium from ore using acids or bases, called leaching). Separation, drying, and packaging are also part of the sequence of uranium processing steps. The choice of the type of processing depends on the nature of the uranium ore and its host rock, as well as environmental, safety, and economic factors. During uranium ore processing, several waste products are created, including tailings or leached residue (the solid waste remaining after recovery of uranium in a processing plant, see Box NS.3), and wastewater.
- ***Reclamation:*** Reclamation and cleanup to return the site to as close as possible to its pre-mining state can occur either while the site is being mined, or after mining and processing operations have ceased. Reclamation includes decontamination and cleanup, such as demolition of buildings and other structures, to prepare the area of the mining site and processing facility for other uses, and on-site or off-site waste disposal. After mining and processing have stopped and the site has been reclaimed, a large volume of low-activity tailings usually remains. In that case, reclamation may include long-term operation and maintenance of water treatment systems or other cleanup technologies.

BOX NS.3. What Are Tailings?

The solid waste remaining after recovery of uranium from uranium ore in a processing plant are the "tailings." Tailings consist of everything that was in the ore except the extracted uranium. Tailings from uranium mining and processing operations contain radioactive materials remaining from the radioactive decay of uranium, such as thorium and radium. Tailings are typically neutralized and compacted to reduce water content, and then stored in tailings impoundment facilities either above or below the local ground surface; modern best practice is for storage below the ground surface.

- ***Long-term stewardship:*** After reclamation, ownership of the parts of the processing site containing tailings passes to either the federal or the state government, which is charged with maintaining the site in perpetuity. Ownership of a mine site on private land typically is retained by the property owner. If the mine is on state or federal land, then the state or federal government will retain ownership. If wastes such as tailings remain at a site, ongoing monitoring, operations, and maintenance will be required, as well as signage and barriers to keep the public from being exposed to any remaining environmental hazards.

URANIUM MINING AND PROCESSING IN VIRGINIA

Extensive site-specific analysis is required to determine the appropriate mining and processing methods for each ore deposit, and therefore it is not possible to predict which uranium mining or processing methods might be used in Virginia without more information on the specific uranium deposits to be mined.

The geological exploration carried out so far indicates that potential uranium deposits in Virginia are likely to be found in hard rock (as opposed to "soft" rock such as coal), making underground mining and/or open-pit mining the mining methods that would probably be chosen. It is likely that many of the technical aspects of mining for uranium would be essentially the same as those for other types of hard-rock mining.

However, uranium mining and processing add another dimension of risk because of the potential for exposure to elevated concentrations of ionizing radiation from uranium and its decay products (see Box NS.4). Assessing the entire life cycle of an operation—from mining to long-term stewardship—is an essential component for planning the extraction of uranium deposits, with each step requiring interaction and communication among all stakeholders.

BOX NS.4. What Is Ionizing Radiation?

Ionizing radiation is energy in the form of waves or particles that have sufficient force to remove electrons from atoms. One source of ionizing radiation is the nuclei of unstable atoms, such as uranium (these unstable atoms are called radionuclides). As the radioactive atoms change over time to become more stable, they emit ionizing radiation and transform into an isotope of another element in a process called radioactive decay. The time required for the radioactivity of each radionuclide to decrease to half its initial value is called the half-life. This radioactive decay process continues until a stable, non-radioactive decay product is formed.

POTENTIAL HEALTH EFFECTS OF URANIUM MINING AND PROCESSING

Uranium mining and processing present a range of potential health risks to the people who work in, or live near, uranium mining and processing facilities. Although some of these health risks would apply to any type of hard-rock mining or other large-scale industrial or construction activity, other health risks are linked to the potential for exposure to radioactive materials that can occur during uranium mining and processing. These health risks mostly affect workers in the uranium mining and processing facilities, but some risks can also apply to the general population.

Health Risks of Radiation Exposure

People are exposed to background levels of ionizing radiation every day. About 50 percent of this radiation comes from natural sources, including radon (see Box NS.5) from rocks and cosmic radiation, and the remaining 50 percent from man-made radiation sources, such as computed tomography (i.e., CT scans) and nuclear medicine (Figure NS.5). However, working in, and to a lesser extent living near, a uranium mining or processing facility could increase a person's exposure to ionizing radiation, thereby increasing the potential for adverse health effects.

Ionizing radiation (hereafter just called radiation) has enough energy to change the structure of molecules, including DNA within the cells of the body. Some of these molecular changes are such that it may be difficult for the body's repair mechanisms to mend them correctly. If a cell is damaged by exposure to radiation and is not effectively repaired, this can lead to uncontrolled cell growth and potentially to cancer. There is a linear relationship between exposure to radiation and cancer development in humans. This means that even exposure to a very small amount of radiation could raise the risk of cancer, but only by a very small amount; increased radiation exposure leads to increased risk. Only a small fraction of the molecular changes to DNA as a result of exposure to radiation would be expected to result in cancer or other health effects.

As well as uranium itself, the radionuclides produced in the uranium decay chain are also a source of radiation. Because uranium-238 is the predominant

BOX NS.5. What Is Radon?

Radon is an odorless, colorless gas produced during the radioactive decay of radium in soil, rock, and water. Protracted exposure to radon and its radioactive decay products can cause lung cancer.

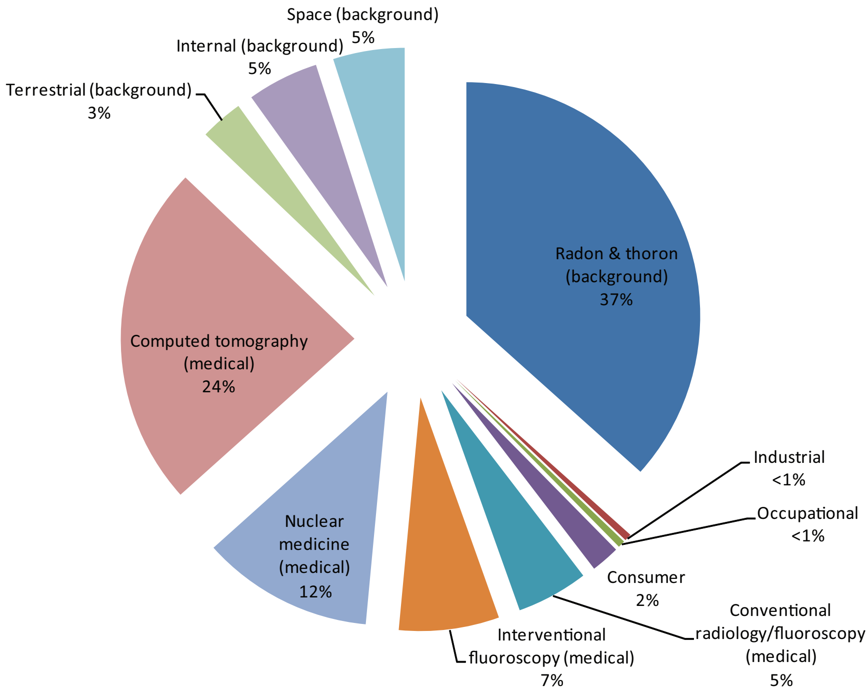

FIGURE NS.5 Contribution of various sources of radiation exposure to the total effective radiation dose equivalent per individual in the United States for 2006. SOURCE: NCRP (2009).

form of uranium found in rock, the radionuclides produced in the uranium-238 decay chain are of the most concern in terms of health risks for the people who work in or live near uranium mines and processing facilities. The key radionuclides in the decay of uranium-238 are thorium, radium, radon, and polonium.

Risk of Radiation Exposure to the General Public

Any exposure to the general population resulting from off-site releases of radionuclides (such as airborne radon decay products, airborne radioactive particles, and radium in water supplies) presents some health risk. People living near uranium mines and processing facilities could be exposed to airborne radionuclides (e.g., radon, radioactive dust) originating from various sources including uranium tailings, waste rock piles, or wastewater impoundments. Exposure could also occur from the release of contaminated water, or by leaching of radioactive materials into surface or groundwater from uranium tailings or other waste mate-

rials. Eventually, released radioactive materials could end up in drinking water supplies or could accumulate in the food chain, ultimately ending up in the meat, fish, or milk produced in the area.

Note that these potential health risks could be substantially mitigated and controlled if uranium mining and processing are conducted according to modern, state-of-the-art methods, including maintaining exposures as low as is reasonably achievable, and if a culture of safety is developed at the mine and processing facility. A robust regulatory framework could help drive such a culture. A mine or processing facility could also be subject to uncontrolled releases of radioactive materials as a result of human error or an extreme event such as a flood, fire, or earthquake.

Risk of Radiation Exposure to Uranium Mine and Processing Facility Workers

Worker radiation exposures most often occur from inhaling or ingesting radioactive materials, or through external radiation exposure. Generally, the highest potential radiation-related health risk for uranium workers is lung cancer associated with inhaling the radioactive decay products of radon gas, which are generated during the natural radioactive decay of uranium.

In 1987, the National Institute for Occupational Safety and Health (NIOSH) in the Centers for Disease Control and Prevention recognized that current occupational standards for radon exposure in the United States do not provide adequate protection for workers at risk of lung cancer from protracted radon decay exposure. NIOSH recommended that the occupational exposure limit for radon decay products should be reduced substantially. To date, this recommendation has not been incorporated into an enforceable standard by the Department of Labor's Mine Safety and Health Administration or the Occupational Safety and Health Administration. Workers are also at risk from exposure to other radionuclides, including uranium itself. In particular, radium and its decay products present a radiation hazard to uranium miners and processors.

Nonradionuclide Health Effects on Mine Workers

Radiation is not the only health hazard to workers in uranium mines and processing facilities. Two other notable risks are the inhalation of silica dust and diesel exhaust fumes. Neither of these is specific to uranium mining, but both have been prevalent historically in the uranium mining and processing industry—silica because uranium ore is frequently (but certainly not always) hosted in silica-containing hard rock; and diesel exhaust fumes because modern mining is typically diesel-equipment intensive.

Silica overexposure can cause the chronic lung disease silicosis as well as other lung and non-lung health problems, while diesel exhaust fumes have been

linked to a variety of adverse respiratory health effects. Of particular importance, however, is the body of evidence from occupational studies showing that both silica and diesel exhaust fumes increase the risk of lung cancer, the main risk also associated with radon decay product exposure. Thus, workers in the uranium mining and processing industry can be co-exposed to three separate lung carcinogens: radon, silica, and diesel exhaust fumes.

All types of mining pose a risk of traumatic injury from accidents such as rock falls, fire, explosions, falls from height, entrapment, and electrocution. In addition, the mining industry has the highest prevalence of hazardous noise exposure of any major industry sector. Processing facility workers are also at risk from exposure to hazardous chemicals used in the uranium recovery process, such as solvents, cleaning materials, and strong acids.

POTENTIAL ENVIRONMENTAL EFFECTS OF URANIUM MINING AND PROCESSING

Documented environmental impacts from uranium mining and processing include elevated concentrations of trace metals, arsenic, and uranium in water; localized reduction of groundwater levels; and exposures of populations of aquatic and terrestrial biota to elevated levels of radionuclides and other hazardous substances. Such impacts have mostly been observed at mining facilities that operated at standards of practice that are generally not acceptable today. Designing, constructing, and operating uranium mining, processing, and reclamation activities according to the modern international best practices noted in this report have the potential to substantially reduce near- to moderate-term environmental effects. The exact nature of any adverse impacts from uranium mining and processing in Virginia would depend on site-specific conditions and on the nature of efforts made to mitigate and control these effects.

Tailings

Uranium tailings present a significant potential source of radioactive contamination for thousands of years, and therefore must be controlled and stored carefully. Over the past few decades, improvements have been made to tailings management systems to isolate tailings from the environment, and below-grade disposal practices have been developed specifically to address concerns regarding tailings dam failures. Modern tailings management sites are designed so that the tailings remain segregated from the water cycle, to control mobility of metals and radioactive contaminants, for at least 200 years and possibly up to 1,000 years. However, because monitoring of tailings management sites has only been carried out for a short period, monitoring data are insufficient to assess the long-term effectiveness of tailings management facilities designed and constructed according to modern best practices.

Furthermore, Virginia is subject to relatively frequent storms that produce intense rainfall. It is questionable whether tailings repositories using state-of-the-art design, modeling, and monitoring design could be expected to prevent erosion and surface-water and groundwater contamination for as long as 1,000 years. Natural events such as hurricanes, earthquakes, extreme rainfall events, or drought could lead to the release of contaminants if facilities are not designed and constructed to withstand such events, or if they fail to perform as designed. The failure of a tailings facility could lead to significant human health and environmental effects. Failure of an aboveground tailings dam, for example, due to flooding, would allow a significant sudden release of ponded water and solid tailings into rivers and lakes.

The precise impacts of any uranium mining and processing operation would depend on a range of specific factors for the particular site. Therefore, a thorough site characterization, supplemented by air quality and hydrological modeling, would be essential for estimating any potential environmental impacts and for designing facilities to mitigate potential impacts. Additionally, until comprehensive site-specific risk assessments are conducted, including accident and failure analyses, the short-term risks associated with natural disasters, accidents, and spills remain poorly defined.

FIGURE NS.6 Underground mine head frame and hoist room. SOURCE: Courtesy Richard Cummins/SuperStock.

REGULATION AND OVERSIGHT

Multiple laws, regulations, and policies apply to uranium mining, processing, reclamation, and long-term stewardship activities in the United States. Understanding the complex network of laws and regulations, which are the responsibility of numerous federal and state agencies, can be difficult.

Making Regulations Proactive

The laws and regulations relevant to uranium mining and processing were enacted over the past 70 years, and many were created following a crisis or after recognition that there were gaps in laws or regulations. Standards contained in regulatory programs represent only a starting point for establishing a protective and proactive program for defending worker and public health, environmental resources, and the ecosystem. A culture is required in which worker and public health, environmental resources, and ecological resources are highly valued, continuously assessed, and actively protected.

Coordinating Regulations Across Multiple Agencies and Levels of Government

Because the laws, regulations, and policies governing uranium mining and processing depend on the type of mining activity and the location of the work, they are spread across numerous federal and state agencies. Mining activities on non-federally owned land are not regulated by federal agencies or programs—state laws and regulations have exclusive jurisdiction over these mining activities. Depending on the particular characteristics of a specific facility, a mix of federal and state worker protection laws, as well as federal and state environmental laws, apply to potential air, water, and land pollution resulting from uranium mining activities.

Limited Experience in the United States and Virginia

The U.S. federal government has had only limited experience regulating conventional uranium mining, processing, and reclamation over the past two decades, with little new open-pit and underground uranium mining activity in the United States since the late 1980s. As shown in Figure NS.2, in 2010 the United States accounted for approximately 3 percent of worldwide uranium production. This relatively low level of recent experience with uranium mining and processing has had a predictable effect on federal laws and regulations—they have remained in place, with very few changes, for the past 25 years. Both the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission have recently revised, or are in the process of revising, some of these regulations. The U.S.

federal government has considerable experience attempting to remediate contamination due to past, inappropriate practices at closed or abandoned sites.

In the recent past, most uranium mining and processing has taken place in parts of the United States that have a negative water balance (i.e., dry climates with low rainfall), and consequently federal agencies have little experience developing and applying laws and regulations in locations with abundant rainfall and groundwater, and a positive water balance (i.e., wet climates with medium to high rainfall), such as Virginia.

Because of Virginia's moratorium on uranium mining, it has not been necessary—or allowed— for the Commonwealth's agencies to develop a regulatory program that is applicable to uranium mining, processing, and reclamation. The state does have programs that cover hard-rock mining and coal mining. At present, there are substantial gaps in legal and regulatory coverage for activities involved in uranium mining, processing, reclamation, and long-term stewardship. Some of these gaps have resulted from the moratorium on uranium mining that Virginia has in place; others are gaps in current laws or regulations, or in the way that they have been applied.

Public Participation in the Regulation of Uranium Mining, Processing, and Reclamation

Because of concerns about the negative effects of uranium mining and processing facilities on human and environmental health and welfare, members of the public often express interest in participating during the regulatory process for such facilities. Requirements for public participation—the two-way exchange between regulators and the public in advance of regulatory decisions so that the public can receive information and make comments—apply to both federal and state regulatory processes.

However, under the current regulatory structure, opportunities for meaningful public involvement are fragmented and limited. Key points in the regulatory process for public participation include the promulgation of regulations of general applicability, the licensing of particular facilities, and the development of post-closure plans for facility reclamation and long-term stewardship. To participate in the regulatory process, members of the public need to be aware of—and be able to respond to—actions such as rulemaking by a range of different state and federal agencies. The "Virginia Regulatory Town Hall" could provide an online means of coordinating information and opinion exchanges about upcoming regulatory changes related to mining. However, at present the Regulatory Town Hall does not offer transparent cross-agency coordination by topic.

During the licensing of particular mining facilities, explicit opportunities for public participation through the Division of Mineral Mining of the Department of Mines, Minerals, and Energy are currently limited to adjacent landowners. The U.S. Nuclear Regulatory Commission (USNRC) has a more robust approach to

public participation in licensing a uranium processing facility. Its regulations require the USNRC to conduct an Environmental Impact Statement, during which pre-licensing public meetings or hearings will be held in the vicinity of the proposed facility. There is no evidence at present that members of the public would be included in deliberations about post-closure plans at the time those plans would be implemented.

BEST PRACTICES

This report provides information to the Virginia legislature as it weighs the factors involved in deciding whether to allow uranium mining. The report describes a range of potential issues that could arise if the moratorium on uranium mining is lifted, as well as providing information about best practices that would be applicable over the full uranium extraction life cycle.

There are internationally accepted best practices, founded on principles of openness, transparency, and public involvement in oversight and decision making, that could provide a starting point for Virginia if the moratorium were to be lifted. For example, guidelines produced by the World Nuclear Association, International Atomic Energy Agency, and International Radiation Protection Association could provide a basis from which specific requirements for any uranium mining and processing projects in Virginia could be developed. Laws and regulations from other states (e.g., Colorado) and other countries (e.g., Canada) provide examples of how certain of these best practices have been incorporated into uranium mining, processing, reclamation, and long-term stewardship programs.

The specific characteristics of any uranium mining or processing facility in the Commonwealth of Virginia would depend on the unique features of the site. Therefore, a detailed compilation of internationally accepted best practices would undoubtedly include many that would not be applicable to a specific situation in Virginia. Accordingly, the report outlines three overarching best-practice concepts, and then provides specific suggestions for best practices that are likely to be applicable should the moratorium on uranium mining in Virginia be lifted:

- *Plan at the outset of the project for the complete life cycle of mining, processing, and reclamation, with regular reevaluations.*

Uranium mining has planning, construction, production, closure, and long-term stewardship phases. Planning should take all aspects of the process into account—including the eventual closure, site remediation, and return of the affected area to as close to natural condition as possible—prior to initiation of any project. Good operating practice is to carry out site and waste remediation on a continual basis during operation of the mine, thereby reducing the time and costs for final decommissioning, remediation, and reclamation.

- *Engage and retain qualified experts.*

Development of a uranium mining project should rely on experts and experienced professionals who are familiar with internationally accepted best practices. This would help to ensure that project development is based on an integrated and cross-disciplinary collaboration encompassing all all aspects of the project, including legal, environmental, health, monitoring, safety, and engineering considerations.

- *Provide meaningful public involvement in all phases of uranium mining, processing, reclamation, and long-term stewardship.*

Meaningful and timely public participation should occur throughout the life cycle of a project, beginning at the earliest stages of project planning. This requires that an environment be created where the public is both informed about, and can comment on, any decisions that could affect their community. One important contribution to transparency is the development of a comprehensive Environmental Impact Statement for all proposed uranium mining, processing, and reclamation activities. Another requirement is that sufficient notice be provided to allow the public time to participate in the regulatory process, and that information be presented clearly so that the public can easily understand it. The public should also be able to understand how their input will be used in the decision-making process.

Specific Best Practices

At a more specific level, the committee also identified a range of best-practice guidelines that would contribute to operational and regulatory planning if the moratorium on uranium mining in Virginia were to be lifted.

Health Impacts

Best practices for safeguarding worker health include the use of personal meters to monitor workers' exposure to radiation, including radon decay products, and a national radiation dose registry to record workers' occupational exposures to ionizing radiation. This would make it easier for workers to track their exposure to radiation as they move from site to site.

Environmental Impacts

A well-designed and executed monitoring plan is essential for gauging the performance of best practices to limit environmental impacts, determining and demonstrating compliance with regulations, and triggering corrective actions if needed. Making the monitoring plan available to the public would help foster

transparency and public participation. Regular updates to the monitoring plan, along with independent reviews, would allow the incorporation of new knowledge and insights gained from analysis of monitoring data. In addition, best practice is to undertake an assessment of the appropriate mitigation and remediation options that would be required to minimize any potential environmental impacts.

Regulation

Regulatory programs are inherently reactive. As a result, the standards contained in regulatory programs represent a starting point for establishing a protective and proactive program for protecting worker and public health, environmental resources, and ecosystems. The concept of ALARA, an acronym for "as low as is reasonably achievable," is one way of enhancing regulatory standards.

CONCLUSION

If the Commonwealth of Virginia removes the moratorium on uranium mining, there are steep hurdles to be surmounted before mining and processing could be established in a way that is appropriately protective of the health and safety of workers, the public, and the environment. There is only limited experience with modern underground and open-pit uranium mining and processing in the United States, and no such experience in Virginia. At the same time, there exist internationally accepted best practices that could provide a starting point for the Commonwealth if it decides to lift its moratorium. After extensive scientific and technical briefings, substantial public input, the review of numerous documents and extensive deliberations, the committee is convinced that the adoption and rigorous implementation of such practices would be necessary if uranium mining, processing, and reclamation were to be undertaken.

1

Introduction

The question of whether uranium mining and processing[1] should be permitted in the Commonwealth of Virginia has aroused strong emotions and reactions, both in favor and opposed. Proponents and opponents in this discussion provided extensive information and briefings to the committee established by the National Research Council (NRC) to provide independent, expert advice to inform decisions about the future of uranium mining in the Commonwealth of Virginia, as it accepted input and deliberated on the scientific, technical, environmental, human health and safety, and regulatory aspects of uranium mining and processing. This committee was specifically charged NOT to make recommendations about whether or not uranium mining should be permitted, and site-specific assessments of individual uranium deposits and occurrences in Virginia were also excluded. Rather, the committee was charged to provide an independent scientific perspective to inform the discussion, as input to those who will make and implement public policy on behalf of the community.

STUDY BACKGROUND

The Coles Hill uranium deposit in Pittsylvania County, south central Virginia, was discovered in 1978 and explored in the 1980s by the Marline Uranium Cor-

[1]The committee uses "processing" throughout the report to encompass all aspects of the process steps that are undertaken to transform raw material extracted from the ground into a granular uranium concentrate product—dominantly U_3O_8 "yellowcake." These steps are sometimes referred to as uranium "milling," although strictly speaking, milling is just one component of several processing steps. Subsequent steps in the nuclear fuel cycle—refining and conversion of the concentrated uranium into uranium dioxide (UO_2) or gaseous uranium hexafluoride (UF_6), enrichment, and ultimately fuel manufacture—are not considered in this report.

poration. In 1982, the Commonwealth of Virginia enacted a moratorium on uranium mining, requiring that additional regulations specific to uranium mining be developed before the Commonwealth could permit uranium mining. Because of a combination of low uranium prices at the time and the moratorium, the deposit at Coles Hill was never mined and the leasing rights were returned to the landowner. Following an increase in uranium prices after 2005, interest in the Coles Hill deposit returned and in 2007 the two families living on and near the deposit formed a company, Virginia Uranium, Inc. The company initiated new exploration of Coles Hill, including new data acquisition and analysis of historical data. Coincident with this new exploration, the Virginia General Assembly, in its 2008 legislative session, began to discuss the potential to establish a Virginia Uranium Mining Commission as an advisory commission in the executive branch of the state government. In November 2008, the Virginia Coal and Energy Commission, established within the legislative branch of the state government, created a Uranium Mining Subcommission to examine the issues related to uranium mining in the Commonwealth and specifically at Coles Hill. The Subcommission expressed interest in a broader study that would encompass the entire Commonwealth of Virginia, and developed a draft statement of task with this broader mandate with input from the NRC. This statement of task was discussed in a public meeting of the Subcommission on May 21, 2009, and the Subcommission voted in favor of the statement of task as the framework for an NRC study.

On August 20, 2009, Delegate Kilgore, of the Virginia Coal and Energy Commission, sent a request to conduct the study to the National Research Council (Appendix A). Additional letters supporting this request were received from U.S. Senators Mark Warner and Jim Webb and from Governor Kaine. In addition to the draft statement of task, the letter from Del. Kilgore indicated that the study would be funded under a contract with the Virginia Center for Coal and Energy Research, directed by Dr. Michael Karmis, at Virginia Polytechnic Institute and State University (Virginia Tech). Funding was provided to Virginia Tech by Virginia Uranium, Inc. Committee members serve *pro bono*, and are not compensated for the considerable time that they devote to committee activities.

DEFINITIONS

The definitions of mining, processing, reclamation, and long-term stewardship—central to many elements of this report—are presented for each of the life-cycle elements:

Mining: Mining includes all the processes by which uranium ore is removed from the ground. There are three types of uranium mining—open-pit mining, underground mining, and in situ leaching/in situ recovery (ISL/ISR). ISL/ISR is also considered to be a processing activity, which occurs in place beneath the Earth's surface. It is possible that some combination of open-pit and underground

mining may be applicable for a single uranium ore deposit. Mining creates several categories of waste, including overburden (the rock that is removed prior to ore recovery that is not processed because of low or negligible recoverable uranium), and wastewater. Mined ore must be transported to a processing facility, usually by truck or conveyor.

Processing: Processing refers to all the steps that follow mining and end with the production of yellowcake, the uranium oxide product (U_3O_8) that is the raw material used for nuclear fuel fabrication. Processing (sometimes referred to as milling) includes ore crushing, grinding, leaching, and uranium recovery from the leached solution. Leaching uses either acidic (usually sulfuric acid) or basic (e.g., sodium carbonate, sodium bicarbonate) solutions. Separation of the uranium from the leached solution—to obtain yellowcake that can be shipped—requires solution purification, precipitation, dewatering, drying, and packaging. During processing, several waste streams are created. These include tailings (the solid materials that remain after leaching) and excess process water.

Reclamation: Reclamation refers to the activities that occur after mining has been completed for a particular area, and includes actions to prepare the mining site and processing facility for eventual reuse for other purposes after the license to mine and process uranium is terminated. Reclamation may include demolition of buildings and other facilities, decontamination and cleanup, and on-site and/or off-site waste disposal.

Long-term stewardship: For mines and processing facilities on federal and state land, the government retains ownership throughout the operation, leasing or permitting use of the land for mineral extraction and processing. After reclamation and other closure/postclosure requirements are met, the government may enforce institutional controls or other restrictions to ensure maintenance and long-term protection of the environment and public health. For operations on private land, state and federal regulations define requirements for the operator or permittee for closure, reclamation, and postclosure protection. After mining and processing have stopped and the site has been reclaimed, a large volume of low-activity tailings usually remains. In that case, long-term stewardship may include operation and maintenance of water treatment systems or other cleanup technologies. Signage and barriers to keep people from being exposed to remaining environmental hazards may be required. Uranium processing facility tailings impoundments require management in perpetuity, with ownership of the area of the impoundment transferred to the state or federal government.

COMMITTEE PROCESS

The National Research Council appointed a committee with broad expertise (Appendix B), encompassing the diverse uranium mining and processing, worker and public health, environmental protection, and regulatory aspects included in the statement of task. The committee met seven times, in Washington, D.C.,

in October and November 2010; in Danville, Virginia, in December 2010; in Richmond, Virginia, in February 2011; in Boulder, Colorado, in March, 2011; in northeastern Saskatchewan (including mine and processing site visits) and Saskatoon, Canada, in June 2011; and in Irvine, California, in September 2011. All except the last of these meetings included time set aside for community input and commentary, including evening "town hall"-style meetings associated with the Danville and Richmond meetings. This challenging schedule was designed to allow the committee to receive briefings regarding the scientific and technical aspects of its charge; to receive input from individuals and community organizations; to deliberate on its findings; and to write its report, all within the tight time constraint of the requirement that the report should be available to inform the Commonwealth of Virginia legislature during its 2011-2012 session.

BOX 1.1
Statement of Task

Uranium mining in the Commonwealth of Virginia has been prohibited since 1982 by a state moratorium, although approval for restricted uranium exploration in the state was granted in 2007. A National Research Council study will examine the scientific, technical, environmental, human health and safety, and regulatory aspects of uranium mining, milling, and processing as they relate to the Commonwealth of Virginia for the purpose of assisting the Commonwealth to determine whether uranium mining, milling, and processing can be undertaken in a manner that safeguards the environment, natural and historic resources, agricultural lands, and the health and well-being of its citizens. In particular, the study will:

(1) Assess the potential short- and long-term occupational and public health and safety considerations from uranium mining, milling, processing, and reclamation, including the potential human health risks from exposure to "daughter" products of radioactive decay of uranium.

(2) Review global and national uranium market trends.

(3) Identify and briefly describe the main types of uranium deposits worldwide including, for example, geologic characteristics, mining operations, and best practices.

(4) Analyze the impact of uranium mining, milling, processing, and reclamation operations on public health, safety, and the environment at sites with comparable geologic, hydrologic, climatic, and population characteristics to those found in the Commonwealth. Such analysis shall describe any available mitigating measures to reduce or eliminate the negative impacts from uranium operations.

(5) Review the geologic, environmental, geographic, climatic, and cultural settings and exploration status of uranium resources in the Commonwealth of Virginia.

REPORT SCOPE AND STRUCTURE

The committee has organized its report in terms of broad topics (e.g., health impacts, environmental impacts) rather than attempting to align the report structure with the numerous elements of the statement of task shown in Box 1.1. The report structure is as follows:

- Chapter 2 briefly describes the physical and social context in which uranium mining and processing might occur—the geological and geographic setting, the environmental and climatic characteristics, and the overarching social setting. This chapter does not, however, address the socioeconomic effects that uranium mining and processing might have on affected communities, because such considerations are beyond the committee's purview.

(6) Review the primary technical options and best practices approaches for uranium mining, milling, processing, and reclamation that might be applicable within the Commonwealth of Virginia, including discussion of improvements made since 1980 in the design, construction, and monitoring of tailings impoundments ("cells").

(7) Review the state and federal regulatory framework for uranium mining, milling, processing, and reclamation.

(8) Review federal requirements for secure handling of uranium materials, including personnel, transportation, site security, and material control and accountability.

(9) Identify the issues that may need to be considered regarding the quality and quantity of groundwater and surface water, and the quality of soil and air from uranium mining, milling, processing, and reclamation. As relevant, water and waste management and severe weather effects or other stochastic events may also be considered.

(10) Assess the potential ecosystem issues for uranium mining, milling, processing, and reclamation.

(11) Identify baseline data and approaches necessary to monitor environmental and human impacts associated with uranium mining, milling, processing, and reclamation.

(12) Provide a nontechnical summary of the report for public education purposes (for example, health and safety issues, inspection and enforcement, community right-to-know, emergency planning).

By addressing these questions, the study will provide independent, expert advice that can be used to inform decisions about the future of uranium mining in the Commonwealth of Virginia; however, the study will not make recommendations about whether or not uranium mining should be permitted nor will the study include site-specific assessments.

- Chapter 3 outlines the global distribution of uranium deposits, describes the existing understanding of potential deposits in Virginia, and outlines the prospectivity status of such deposits. This chapter also provides a general overview of uranium reserves, markets, and prices.
- Chapter 4 describes technical aspects of uranium mining, processing, and reclamation as they might be applied in Virginia, covering the full range from initiation of mining through to decommissioning and legacy management. Although many of the techniques described in this chapter apply to hard-rock mining in general, there is specific focus on aspects that are uranium-specific. Note that surface and underground mining techniques are primarily dealt with in this chapter—and in the report in general—with ISL/ISR mining of uranium only briefly described for completeness, because it is unlikely to be applicable in Virginia as a consequence of the particular geological characteristics of the Commonwealth.
- Chapter 5 outlines adverse human health effects that can potentially arise from uranium mining and processing—encompassing both occupational health and safety and broader public health perspectives—as well as brief descriptions of potential human health effects that are not specific to uranium mining. Best practices that might be applied to address and mitigate some of the potential health effects are discussed in Chapter 8.
- Chapter 6 outlines adverse environmental effects that can arise from uranium mining and processing—potential air, water, soil, and ecosystem impacts beyond the immediate borders of a uranium mining and processing facility.
- Chapter 7 describes the existing federal and Virginia legal environment, encompassing laws, regulations, and oversight through the full range from mining and processing, through site reclamation, to long-term stewardship.
- Chapter 8 addresses the charge to describe "best practices" that might apply to a uranium mining and processing facility in Virginia, bringing together aspects touched upon in Chapters 4 to 7.

This task statement requires that the committee consider the entire Commonwealth of Virginia in its assessment and analysis. However, as outlined in Chapter 3, the uranium deposit at Coles Hill is the only known potentially economically viable uranium resource in Virginia. Consequently, although the characteristics of all of Virginia are examined in the descriptive elements of this report, there is slightly greater focus on the southern part of Virginia in the vicinity of Coles Hill. In addition, the committee recognized that some of the potential effects of uranium mining and processing—both negative and positive—would inevitably extend across state borders; however, the statement of task clearly restricts the committee's focus to Virginia alone and therefore such potential effects were not explicitly considered, nor was input from citizens and interest groups in adjacent states sought.

2

Virginia Physical and Social Context

Key Points

- Virginia has a diverse natural and cultural heritage, and a detailed assessment of both the potential site and its surrounding area (including natural, historical, and social characteristics) would be needed if uranium mining and processing were to be undertaken. Virginia's natural resources include a wide range of plants, animals, and ecosystems, a large number of which are currently under significant stress.
- The demographic makeup of the state varies greatly, both among and within its physiographic provinces.
- Virginia is subject to extreme natural events, including relatively large precipitation events and earthquakes. Although very difficult to accurately forecast, the risks and hazards associated with extreme natural events would need to be taken into account when evaluating any particular site's suitability for uranium mining and processing operations.

This chapter presents a summary of the overarching physical and social context in which any uranium mining and processing in Virginia would occur. The general geography and geology are discussed first, followed by information on mining in the state. Next, the climate, ecology, and the surface and groundwater characteristics of Virginia's different regions are introduced. Finally, the broad social context is presented, with particular emphasis on areas that might be mined for uranium.

GEOLOGY AND GEOGRAPHY OF VIRGINIA

The Commonwealth of Virginia spans 755 km (469 miles) west to east and 323 km (201 miles) north to south, encompassing a total area of 110,785 square km (42,774 square miles) (Fleming et al., 2011). It is divided into five physiographic zones (Figure 2.1)—the Appalachian Plateau, Valley and Ridge, Blue Ridge Mountains, Piedmont, and Coastal Plain. This physiographic zonation closely follows the overall geology, shown in Figure 2.2. While uranium-bearing rocks occur throughout Virginia, the Piedmont contains most of the identified possible resources for uranium mining. These occurrences are discussed in more detail in Chapter 3.

Physiographic Provinces

The **Appalachian Plateau** is the westernmost geographic region in Virginia, occurring only in a small area in the southwest. This province, part of the northern Cumberland Mountains, has rough topography with average elevations between 305 and 914 m (1,000-3,000 ft) (Bailey, 1999a). The region is underlain by flat to gently sloping Mississippian to Pennsylvanian (299-359 million years old [My])

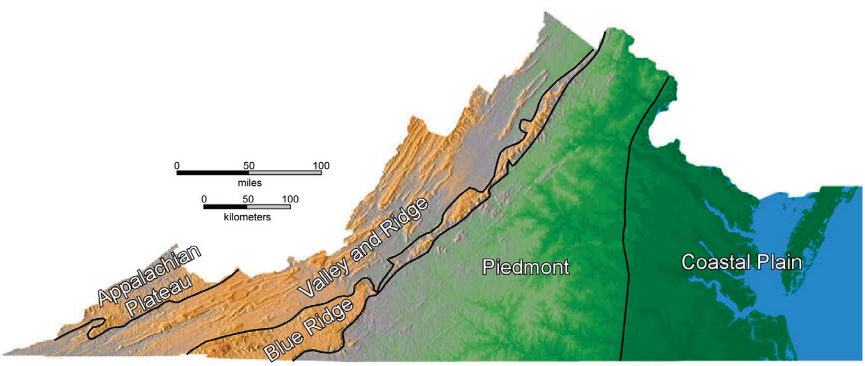

FIGURE 2.1 The five physiographic regions of Virginia. SOURCE: Modified from Bailey (1999a).

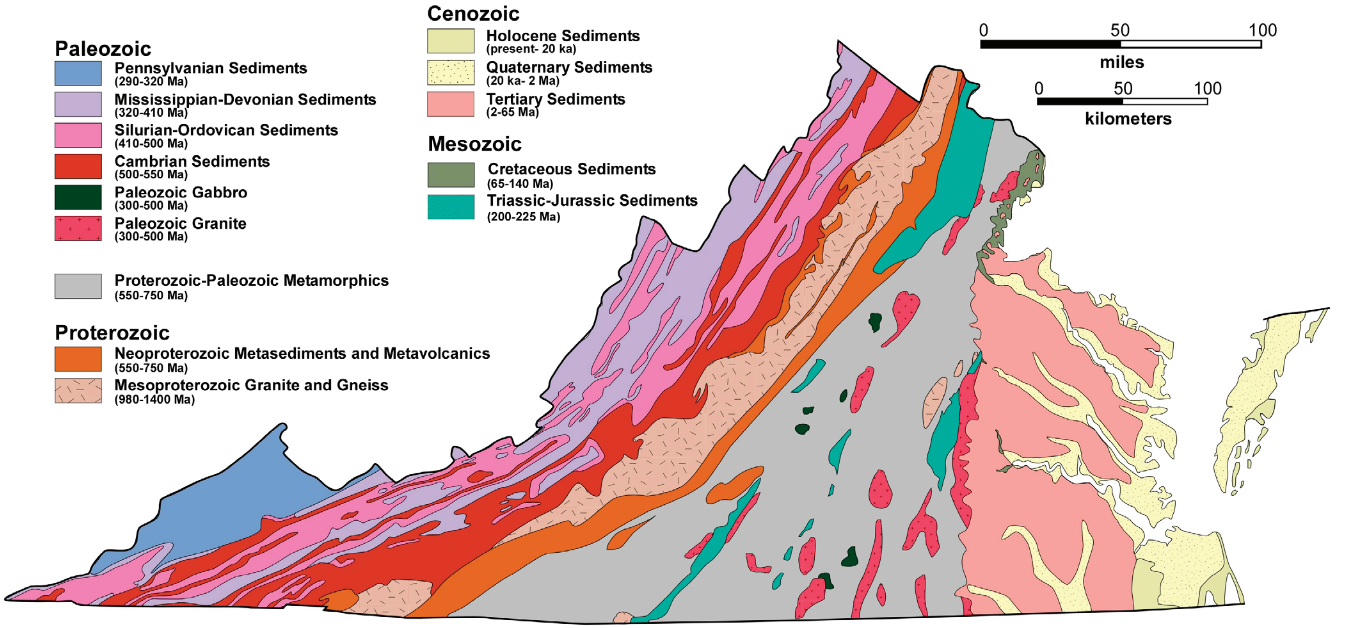

FIGURE 2.2 Simplified geological map of Virginia. Virginia's geology is extremely diverse, resulting from a long geological evolution starting at least some 1.44 billion years (Ga) ago with Proterozoic rocks in the Blue Ridge and Western Piedmont provinces, through four successive episodes of mountain building (orogenic cycles): the Grenville Orogeny at about 1.1 Ga, the Taconic Orogeny at about 0.45 Ga, the Acadian Orogeny at about 0.38 Ga, and finally the Alleghenian Orogeny at about 0.32 Ga. SOURCE: Modified from Bailey (1999b).

sedimentary rocks including sandstone, coal, and shale. In addition to coal, the Appalachian Plateau hosts natural gas resources (VA DMME, 2008). Stream erosion has dissected much of the original plateau morphology (Bailey, 1999a).

The **Valley and Ridge** region, which lies to the east of the Appalachian Plateau, is composed of tectonically folded Cambrian to Mississippian (318-542 My) sedimentary rocks, including limestone, dolomite, sandstone, and shale (VA DMME, 2008). These rocks have undergone differential weathering to produce the linear chains of valleys and ridges that give this region its name.[1] This region also contains distinctive karst landforms, created by the interaction of carbonate rock with water, and associated cave systems, extensive subsurface drainage, and convoluted stream patterns.[2] This region is dominated by the Shenandoah Valley, with the ridges of the Allegheny Mountains extending west of the Valley to Virginia's border.

The **Blue Ridge** physiographic province bounds the Valley and Ridge to its east. The Blue Ridge Mountains encompass the highest relief in Virginia, with typical elevations of 457-1,280 m (1,500-4,200 ft), rising up to Mt. Rogers' 1,746-m (5,729-ft) height. This narrow region has Mesoproterozoic (980-1,440 My) bedrock composed of granite and gneiss, and Neoproterozoic (550-750 My) metasediments and metabasalts (greenstones or greenschists) (Bailey, 1999b; VA DMME, 2008). The northern part of the Virginia Blue Ridge has rough, steep terrain, while the southern Blue Ridge is more plateau-like (Bailey, 1999a).

The **Piedmont**, which lies east of the Blue Ridge Mountains, is the largest physiographic region in the state and also the most variable in terms of geology and geography. The Piedmont is underlain by igneous (granite) and metamorphic (gneiss, schist, and slate) rocks, mostly of Proterozoic (542-1,440 My) and Paleozoic (542-251 My) age (Bailey, 1999b; VA DMME, 2008). The metamorphic grade of the rocks increases from west to east—the Western Piedmont has low- to medium-grade metasedimentary rocks, the Central Piedmont has low- to high-grade metasedimentary and metavolcanic rocks, and the Eastern Piedmont has mostly high- to very high-grade metasedimentary and metavolcanic rocks (VA DMME, 2008). The Goochland Terrain, located in the Eastern Piedmont, has very high-grade Proterozoic rocks (granite, gneiss, and amphibolites) that may have been ancient North American basement (VA DMME, 2008). The bedrock is often covered by saprolite, rock that has been chemically weathered due to the humid climate.[3] There are also some areas of sedimentary rock, including sandstone, shale, and conglomerate[4] (Bailey, 1999b). This region, a transitional area between flat land and mountains, consists of plateaus, rolling hills, and ridges.

[1]http://web.wm.edu/geology/virginia/?svr=www.
[2]http://www.dcr.virginia.gov/natural_heritage/karsthome.shtml.
[3]http://web.wm.edu/geology/virginia/?svr=www; accessed August 2011.
[4]http://www.deq.virginia.gov/gwpsc/geol.html; accessed August 2011.

The **Coastal Plain**, Virginia's easternmost physiographic region, is bounded by the Chesapeake Bay and Atlantic Ocean to the east and the Piedmont region to the west. It is separated from the Piedmont by the "Fall Line." This hypothetical north-south line is characterized by non-navigable waterfalls, where east-flowing rivers leave the hard bedrock of the Piedmont for the unconsolidated sediments of the Coastal Plain. These sediments consist mainly of Tertiary, Quaternary, and Holocene (i.e., deposited between 65 My and the present) gravel, sandstone, mudstone, claystone, and marl (lime-rich mudstone), created through alternating periods of sea-level rise and fall (Bailey, 1999b). The province is divided into gently sloping uplands, lowlands with very little relief near the Chesapeake Bay, and barrier islands and salt marshes (Bailey, 1999a). The Coastal Plain contains heavy mineral sand deposits, which are mined for titanium (VA DMME, 2008).

Economic Geology

Virginia has an active mining industry, exploiting coal, oil and gas, and mineral resources. Coal provides the state with its most economically valuable mineral resource[5]—Virginia was responsible for 2 percent of total U.S. coal production in 2009, amounting to 21.2 million tons with an estimated value of $1.6B (USEIA, 2009). The oil and gas industry, valued at $518M in 2009, produced 140.7 million cubic feet of gas and 11,430 barrels of oil. Mineral mines had production of 56 million tons, with an estimated value of $978M. Coal and mineral mining employed over 7,000 people in 2009 (Spangler, 2011).

The most active coalfields in Virginia occur in the Appalachian Plateau province, a part of the Appalachian Coal region stretching from Alabama to Pennsylvania. The entire Appalachian Coal region produces approximately one-third of the nation's coal,[6] although only a small portion of the coalfield lies within Virginia's borders. There are also smaller, lower-quality coalfields in the Valley and Ridge and Piedmont provinces.[7] The Appalachian Plateau region produces high-quality, bituminous coal, and is also responsible for most of the oil and gas produced in the state.[8] Gas production is concentrated in the northern Appalachian Plateau and includes both conventional gas and coal-bed methane.[9]

Virginia mineral resources cover a broad spectrum—sand, gravel, and stone; heavy mineral sands (rutile/titanium, ilmenite, zircon, leucoxene); and feldspar, industrial sand, clays, kyanite, and vermiculite.[10] In 2003, mineral resources valued at $727M accounted for 35 percent of all mining; of that, 65 percent ($479M) was related to the mining of crushed stone (Gilmer et al., 2005). During

[5]http://www.dmme.virginia.gov/DMR3/coal.shtml.
[6]http://www.eia.gov/energyexplained/index.cfm?page=coal_where.
[7]http://www.dmme.virginia.gov/DMR3/coal.shtml.
[8]http://www.dmme.virginia.gov/DMR3/energyresources.shtml.
[9]http://www.dmme.virginia.gov/DMR3/naturalgas.shtml.
[10]http://www.dmme.virginia.gov/DMR3/mineralresources.shtml.

that time, Virginia was the nation's second-highest producer of feldspar, ilmenite, zirconium, and vermiculite, and the only state to mine kyanite. Sand and gravel mining occurs mainly in the Coastal Plain physiographic province, while crushed stone mining occurs throughout the state. Clay minerals, shale, and slate are mined in western and central Virginia, including the Piedmont province; shale is mined in the Danville Triassic Basin in Pittsylvania County. Industrial lime is mined mainly in the Valley and Ridge region (Gilmer et al., 2005).

Geological Natural Hazards

In August 2011, a 5.8-magnitude earthquake centered near Mineral, Virginia, caused widespread shaking along the eastern United States, and was felt as far away as central Georgia and southeastern Canada.[11] Early post-earthquake estimates are for > $100M in damage, and for the first time in the United States a nuclear power facility was shaken by more than its design capacity. The earthquake occurred within the Central Virginia Seismic Zone, an area of seismicity known to be responsible for small and moderate earthquakes since the 1700s. Prior to 2011, the largest recorded earthquake in Virginia was a 4.8-magnitude earthquake in 1875, and another more recent earthquake—in December 2003—registered at 4.5 magnitude. All these earthquakes were located in the Central Virginia Seismic Zone.

Although major earthquakes are a rare occurrence in Virginia, landslides and debris flows are more common, particularly in the rugged topography of the Appalachian Mountains, and pose significant geohazard risks. The largest known prehistoric landslides in the eastern part of North America are located in the Virginia Appalachians (NRC, 2004). Debris flows, discussed in more detail below, have had devastating impacts on mountainous parts of the state. More than 50 historical debris flows, occurring between 1844 and 1985, have been mapped in the Appalachians; most are located within the foothills of the Blue Ridge Mountains in central Virginia (USGS, 1996). Recurrence intervals for debris flows in river basins in this region are less than 2,000 to 4,000 years, and account for approximately half of the erosion in the area (Eaton et al., 2003).

CLIMATIC AND ENVIRONMENTAL CHARACTERISTICS

Climate

Virginia has a humid subtropical climate, with an average annual rainfall of 108.5 cm (averaged from 1895 to 1998). The state has five climate regions that are similar to the physiographic regions, with three main factors influencing the climate—the Gulf Stream and the Atlantic Ocean, the Blue Ridge and Appa-

[11] http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/se082311a.php#summary.

TABLE 2.1 Average Rainfall and Temperature by Physiographic Province

Province	Average Rainfall (cm/yr)	Average Temperature (°C)
Appalachian Plateau	105-125	13
Valley and Ridge	76-114	4-14
Blue Ridge	100-130	10-16
Piedmont	114-140	14-18
Coastal Plain	110	13-14

NOTE: Average rainfall data such as these do not reflect whether the rainfall occurs steadily through the year, or is more concentrated in larger rainfall events.
SOURCE: Data from McNab and Avers (1994).

lachian Mountains (including the Blue Ridge Mountains), and the convoluted pattern of rivers and streams that influence moist airflow throughout the state (Hayden and Michaels, 2000). Climate and annual rainfall totals can vary dramatically through the five climate regions (Table 2.1), with total yearly rainfalls that can vary by over 65 cm between the Shenandoah Valley and the mountainous area in the southwestern part of the state (Hayden and Michaels, 2000).

Virginia is subject to extreme weather events—hurricanes and tropical storms, thunderstorms, and heavy rainfall and snowfall. In the period from 1933 to 1996, 27 hurricanes and/or tropical storms made landfall in Virginia,[12] bringing with them the threats of flooding, high winds, and tornadoes. Ten to forty percent of the state's rainfall in the month of September can be attributed to hurricanes or tropical storms (Hayden and Michaels, 2000). Hurricane Camille,[13] one of the "most intense" tropical storms ever recorded in Virginia (USDOC, 1969), produced heavy rainfall of up to 790 mm (31.1 in) as it crossed the state in 1969, and caused intense flash flooding that led to the loss of many lives. Nelson County, in the eastern Blue Ridge, was most severely affected (Bechtel, 2006). A storm system in the Blue Ridge Mountains on June 27, 1995, produced rainfall of 600 mm (23.6 in) in a 6-hour period that caused a peak flood discharge of 3,000 m^3/s (106,000 cfs) on the Rapidan River (drainage area of 295 km^2). The flood caused more than 500 separate landslides, debris flows, and debris avalanches, making the storm comparable to the most severe ever recorded in the region (Smith et al., 1996). More recently, Hurricane Fran crossed the Piedmont as it moved north-northwest across Virginia in 1996, bringing up to 40 cm of rain from the combination of two weather systems (Connors, 2008). In 2011, Hurricane Irene caused wind gusts up to 114 km/hr (71 mph) and 1.0 to 1.4 m (3.5 to 4.5 ft) storm surges across eastern Virginia, including a 2.3-m storm surge in Norfolk.[14]

[12]http://www.erh.noaa.gov/akq/hist.htm.
[13]http://www.nhc.noaa.gov/HAW2/english/history.shtml#camille.
[14]http://hamptonroads.com/2011/08/mcdonnell-hurricane-irene-could-bring-historic-storm-surges.

TABLE 2.2 Land Cover of Virginia in Approximate Square Kilometers and Percentage

Land Cover Type	Square Kilometers	Percentage
Open water	8,650	7.75
Developed	3,750	3.38
Barren	200	0.20
Forest	68,350	61.31
Agriculture/open	26,350	23.65
Wetland	4,150	3.71

SOURCE: Vogelmann et al. (2001); VA DGIF (2005).

Land Cover

Almost 62 percent of the Commonwealth of Virginia is covered in forest, equaling 15.72 million acres of forestland.[15] The Coastal Plain region is dominated by loblolly pine and hardwood (McNab and Avers, 1994), with loblolly pine and longleaf in the southeastern part of the area (Woodward and Hoffman, 1991). The Piedmont is predominately oak-hickory (north) and pine (south) (VA DGIF, 2005), and the Blue Ridge and Valley and Ridge are mostly composed of oak and oak-pine, with a few areas of spruce, fir, and hardwoods (Woodward and Hoffman, 1991). Ninety-three percent of the Appalachian Plateau is forested, and is composed of a mix of conifers and hardwoods (Woodward and Hoffman, 1991). Other land cover in Virginia is described in Table 2.2. The value of pine and hardwood forests contributed over $207M to the Virginia economy in 2008.[16]

Plant and Animal Species

There are 3,388 native species of plants and animals documented in Virginia (Stein et al., 2000). Of these, 47 animal species and 17 plant species are on the federal endangered or threatened species lists, and 115 animal and 27 plant species are listed by the state as endangered or threatened (Townsend, 2009; Roble, 2010). Based on state criteria, 52 percent of the natural community types in Virginia are either critically imperiled or imperiled, and another 21 percent are vulnerable; according to federal criteria, 40 percent are critically imperiled or imperiled and 20 percent are vulnerable (Fleming and Patterson, 2010). Mineral extraction primarily related to coal and gravel mining is cited as one of the major threats to conservation (VA DGIF, 2005).

[15]http://www.dof.virginia.gov/resinfo/forest-facts.shtml; accessed August 2011.
[16]http://www.dof.virginia.gov/econ/statewide-value-volume.shtml.

The Coastal Plain region provides habitats for many species, including 235 species of greatest conservation need[17] (VA DGIF, 2005). The Piedmont province has 157 species of greatest conservation need, and ~5 percent of the region is within a specifically designated conservation area (VA DGIF, 2005). The mountainous Blue Ridge has 174 species of greatest conservation need, 28 percent of the region is part of a conservation land, and only 2 percent of the area is developed (VA DGIF, 2005). The Valley and Ridge province has 384 species and the Appalachian Plateau contains 101 species of greatest conservation need (VA DGIF, 2005). The Coastal Plain, Blue Ridge, and Valley and Ridge provinces are crucial as stopover habitat for migratory birds, because of their locations along the East Coast and in the middle of the Appalachians, respectively (Hill, 1984).

Surface Water

Surface water conditions in Virginia vary over space and time, reflecting variations in precipitation, evapotranspiration, relative wetness, watershed area, and the hydrogeological properties of the different watersheds within the state. The seven major river watersheds have mean annual runoff that varies only modestly (0.33-0.58 m), with somewhat higher rates measured in watersheds that drain to the Gulf of Mexico (e.g., New and Powell rivers) compared with those that drain to the Atlantic Ocean. This pattern is most probably due to higher precipitation to the western, windward side of Virginia's mountainous terrain (Table 2.3). Maximum annual runoff varies modestly (less than a factor of two) among these basins as well, although minimum annual runoff is somewhat more variable (Table 2.3). Although differences between maximum and minimum annual runoff can vary dramatically from year to year (i.e., by a factor of between 3 and 10) for individual basins in the state, it is important to note that annual runoff is a positive quantity, and this has important ramifications for uranium mining and processing in Virginia. There is additional discussion of this topic in Chapter 6.

In the Coastal Plain and the Piedmont, streams are small to intermediate, with low flow rates in the Coastal Plain and low to intermediate flow rates in the Piedmont (McNab and Avers, 1994). The Blue Ridge region mostly has high-gradient, year-round streams (Woodward and Hoffman, 1991), whereas streams in the Valley and Ridge region are small and seasonal. The Appalachian Plateau has small-to-medium, year-round, moderate-flow streams occurring at medium to high density (McNab and Avers, 1994).

As noted earlier, Virginia is also subject to extreme precipitation events associated with convection, frontal activity, tropical storms, and hurricanes that can cause both local flash flooding and river flooding. The central Appalachians have been subject to extreme precipitation that was greatly enhanced by orographic effects (e.g., the remnants of Hurricane Camille in 1967; the Rapidan storm of

[17] See http://bewildvirginia.org/species/; accessed October, 2011.

TABLE 2.3 Mean, Minimum, and Maximum Annual Runoff for Seven Major Watersheds in Virginia Based on Long-Term USGS Discharge Data.

Watershed	Mean Annual Runoff ($m/yr{\cdot}m^{-2}$)	Min. Annual Runoff ($m/yr{\cdot}m^{-2}$)	Max. Annual Runoff ($m/yr{\cdot}m^{-2}$)
Potomac River near Washington, D.C. (adj.)	0.354	0.139	0.727
Rappahannock River near Fredericksburg, VA	0.363	0.095	0.712
Mattaponi River near Beulahville, VA	0.328	0.047	0.695
James River near Richmond, VA	0.359	0.109	0.634
New River at Glen Lyn, VA	0.455	0.230	0.686
Powell River near Jonesville, VA	0.576	0.236	1.020
Roanoke (Staunton) River at Randolph, VA	0.334	0.099	0.597

SOURCE: http://waterdata.usgs.gov/va/nwis/sw; accessed September 2011.

1995), in which air masses interacted with the Blue Ridge Mountains to produce record flood discharges, debris flows and avalanches, landslides, extensive property damage, and loss of life (Smith et al., 1996; Pontrelli et al., 1999; Sturdevant-Rees et al., 2001; Hicks et al., 2005).

The combination of extreme precipitation and topography puts much of Virginia at extremely high risk for flooding, relative to the rest of the United States. Virginia's mean annual flood potential exceeds 142 m^3 s^{-1}/780 km^2 (5,000 ft^3 s^{-1}/300 mi^2), while areas west of the Blue Ridge exceed 227 m^3 s^{-1}/780 km^2 (8,000 ft^3 s^{-1}/300 mi^2). Virginia's 10-year flood potential exceeds 283 m^3 s^{-1}/780 km^2 (10,000 ft^3 s^{-1}/300 mi^2), with some high-elevation locations in the western part of the state exceeding 566 m^3 s^{-1}/780 km^2 (20,000 ft^3 s^{-1}/300 mi^2) (van der Leeden et al., 1990). These values are much higher than the mean annual (<57 m^3 s^{-1}/780 $km^{2)}$ and 10-year (<142 m^3 s^{-1}/780 km^2) flood potentials for much of the western United States, where most uranium mining has occurred in the past.

Computations of predicted peak discharge (based on equations developed from empirical data from Virginia watersheds by Bisese, 1995) also reveal far greater spatial variability across the state than that associated with annual runoff. For example, the predicted 10-year peak discharge for a 780-km^2 (300-mi^2) watershed in the Coastal Plain is 103 m^3 s^{-1}, compared with a value of 284 m^3 s^{-1} for a comparable watershed in the Southern Piedmont. Overall, these computations show spatial variability of about a factor of six across the region for both 10- and 100-year peak discharges (Table 2.4), with the highest peak discharges associated with watersheds draining mountainous parts of the state (e.g., Blue Ridge and Appalachian Plateau), intermediate peak discharges associated with the Piedmont and Valley and Ridge regions, followed by the lowest values for the Coastal Plain (Table 2.4). The relatively rare, but extreme, precipitation events that lead to major floods have important ramifications for uranium mining and processing (see further discussion in Chapter 6).

TABLE 2.4 Predicted Peak Discharge Values for Rural, Unregulated Streams in Virginia[a]

Region	10-Year Discharge (cms)	100-Year Discharge (cms)
Coastal Plain	103	211
Southern Piedmont	284	583
Northern Piedmont	480	1,078
Blue Ridge	484	1,006
Southern Valley and Ridge	345	557
Central Valley and Ridge	476	891
Northern Valley and Ridge	472	1,048
Appalachian Plateau	657	1,144

[a]Based on Equations in Bisese (1995). Computations assume a typical 300 mi^2 ungaged watershed located in each of eight different physiographic regions.

Groundwater

Groundwater is an important resource throughout Virginia. Although a greater volume of the state's water is taken from surface water sources, there are more users of groundwater than surface water (VA DEQ, 2008). In 2008, groundwater withdrawals constituted 22 percent of the freshwater used in Virginia (USGS, 2008). The majority of groundwater withdrawals are for manufacturing and public water supply, with smaller withdrawals for agriculture, irrigation, commerce, and mining (Figure 2.3). About 22 percent of Virginia's population uses privately owned domestic wells for their drinking water, with heavier use in rural locations (Figure 2.4). In many counties, more than 60 percent of the people rely on private wells for their water (USGS, 2005).

Virginia is host to three principal aquifer systems (Trapp and Horn, 1997): Coastal Plain, Piedmont and Blue Ridge, and Valley and Ridge. In addition, a small portion of western Virginia is host to the Appalachian Plateau aquifer system. In general, the groundwater resources of the state are not well characterized. There is better understanding of the Coastal Plain aquifer system than the other systems in the state, in part because of the high productivity and demand placed on the system. The majority of Virginia's observation wells (381 out of 411) are located in the Coastal Plain and in the northern Shenandoah Valley (Valley and Ridge); the remainder of the state is covered by only 30 wells (USGS, 2008; D. Nelms, USGS, personal communication, 2010). As mentioned earlier, there are regional differences in the geology of each aquifer system. The Coastal Plain aquifer hosts unconsolidated to semi-consolidated sedimentary rocks; the Piedmont and Blue Ridge aquifer is in crystalline rock, the Valley and Ridge aquifer hosts folded consolidated sedimentary rocks, and the Appalachian Plateau aquifer is in consolidated sedimentary rocks. In addition, there can be important differences at the local scale within each region.

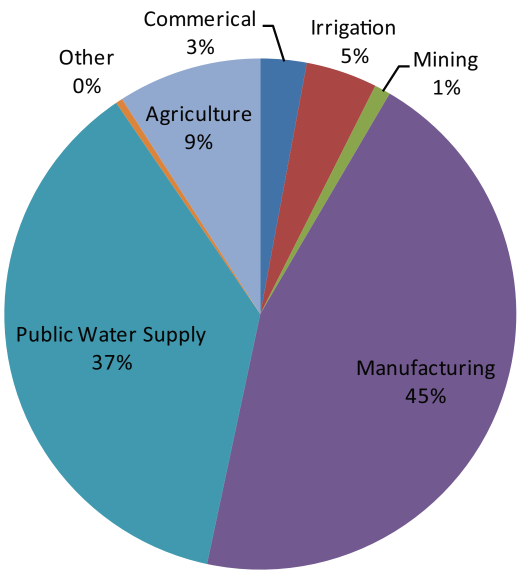

FIGURE 2.3 **Average groundwater use in Virginia by category, 2003-2007. "Manufacturing"** includes operations such as paper mills, food processors, drug companies, furniture, and concrete companies; "public water supply" includes municipal and private water purveyors; "agriculture" includes operations such as commodity farms, fish farms, and hatcheries; "irrigation" withdrawals are used to promote growth in crops such as tobacco, corn, soybeans, turf grass, and ornamental nursery products; "commercial" operations include golf courses, local and federal installations, hotels, and laundromats; and "mining" includes operations such as sand, rock, and coal companies. SOURCE: Based on 2010 data from VA DEQ.

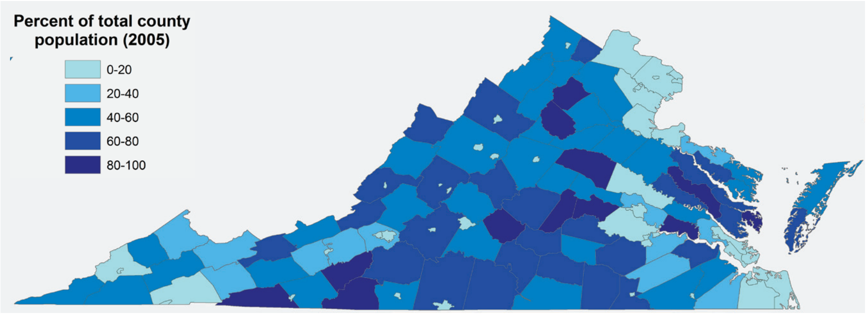

FIGURE 2.4 Proportion of Virginia population served by domestic wells in 2005, by county. Domestic wells supply drinking water for more than one in five Virginians. SOURCE: USGS (2005).

The Coastal Plain's alternating layers of sand, gravel, silt, shell fragments, and clay are host to the majority of the state's groundwater use. Water quality is generally good, although there are local areas of saltwater intrusion and elevated levels of iron and hydrogen sulfide. The high permeability and water storage in the Coastal Plain have led to heavy usage, which places the aquifer system, particularly the unconfined upper aquifer, at high risk for degraded water quality. Aquifers in the Coastal Plain historically have shown high yield and have been able to support much of the area's water demand. Increasing demand, however, has led to declining water levels—in the Middle Potomac aquifer, for example, water levels are dropping at the rate of about 2 ft/yr (VA DEQ, 2008).

The Piedmont and Blue Ridge aquifer system comprises igneous and metamorphic rock with sedimentary rock at the western margin. Water primarily is held in fractures and faults that decrease in number and size with increasing depth. Consequently, groundwater supply is limited, although wells that intercept well-connected fracture networks may sustain yields suitable for smaller scale domestic or agricultural use. The potential risk to groundwater quality from introduced contaminants depends on fracture geometry. Springs are common in the western portion of the area. High permeability within the transition zone between the saprolite and bedrock makes this an area highly conducive to water flow and transport of dissolved materials, including contaminants. The transition zone stores a large fraction of the water in these systems.

The Valley and Ridge aquifer system is hosted by consolidated sedimentary rocks and carbonate rock. The most productive aquifers (150 to 1,000 gallons per minute [gpm]) are in carbonate rock, although yield depends on the degree of fracturing and development of solution cavities. The connection between groundwater and surface water in this region is readily apparent through its karst topography, where surface water directly recharges groundwater through sinkholes and capture of surface streams to the subsurface.

The Appalachian Plateau aquifer system is hosted by sandstone, shale, and coal with some carbonate units. Well yields from the sandstones are suitable for domestic supply (<12 gpm) but not heavy development, while carbonates can yield up to 50 gpm. Water quality varies with location and locally can be sulfur- and iron-rich, particularly in coal mining areas.

SOCIAL CHARACTERISTICS

In 2010, Virginia had a population of slightly over 8 million people (U.S. Census Bureau, 2010), with a population density of 202 people per square mile of land. The settlement patterns of Virginia vary greatly, however, and have been driven partly by its geography.

The Coastal Plain makes up approximately one-fifth of Virginia's land area. This province was the first to be settled by Europeans, primarily from England, with African slaves imported for agricultural labor. Today, with the exception

of the Eastern Shore peninsula, the Coastal Plain has a fairly high population density, especially around Arlington and Alexandria (suburbs of Washington, D.C.), Richmond (Virginia's capital), and the coastal cities of Hampton, Newport News, Norfolk, Portsmouth, and Virginia Beach. This region is the most densely populated of the Commonwealth's five physiographic regions.

The Fall Line—the arbitrary western boundary of the Coastal Plain at the transition to steeper topography—effectively contained early European settlement to coastal area, because easy boat access was barred to the west. It also separated the Algonquian-speaking tribes of the Coastal Plain from the Siouan- and Iroquoian-speaking tribes in the Piedmont region to the west. Like the Coastal Plain, the Piedmont was settled primarily by the English with imported African slaves, but it was—and remains—less densely settled. Because the Piedmont contains most of the known potentially viable uranium deposits in the state, it is described in greater detail later in this chapter.

The narrow Blue Ridge region—the Blue Ridge Mountains—provides recreational opportunities along and near the Blue Ridge Parkway. The Shenandoah Valley in the Valley and Ridge province is part of the Great Appalachian Valley. Composed of a series of valleys that run from Quebec to Alabama, the Great Valley was a major north-south passageway for Native Americans and white settlers. The Shenandoah Valley, which saw white settlers—primarily Germans and Scots-Irish—in the early 1700s, has fertile soil and a tradition of small farms (farm animals, grain, orchards) interspersed with towns and small cities. The heavily traveled I-81 highway traverses the Shenandoah Valley. The western Valley and Ridge, with its rugged ridges, is more remote and both less populous and less prosperous.

The Appalachian Plateau, isolated from the rest of Virginia by the Appalachian Mountains, is sparsely populated and more economically challenged. Its primary industry is coal mining. However, according to a recent report by the U.S. Energy Information Administration, none of Virginia's coal mines can be considered to be major; as of 2009, none was producing more than 4 million short tons annually (USEIA, 2009).

The Piedmont Region

Nineteen of Virginia's 95 counties are wholly contained within the Piedmont region, with parts of other counties around its periphery. Of the 19 counties, 5 are located in the northern Piedmont and 14 in the southern Piedmont, with the James River acting as an informal boundary. In 2010, the total population of these 19 counties, together with two independent cities (Martinsville and Danville), was 611,446, resulting in an average population density of 70 people per square mile. The population in the northern Piedmont is considerably denser than the southern Piedmont—in 2010, the former had an average of 90 people per square mile; the latter, 65 people per square mile. The northern Piedmont is contained roughly within a triangle defined by Washington, D.C. to the north, Charlottesville to the

west, and Richmond to the east. Its proximity to these metropolitan areas and its natural beauty and rich history have helped make the northern Piedmont a recreational destination and refuge for nearby urbanites. In contrast, the southern Piedmont is lagging behind in wealth and population growth. Traditionally reliant on tobacco growing, it became a center for textile manufacturing in the 20th century but has largely lost that industry. While population grew aggressively during the 2000-2010 decade in some areas of Virginia, including the northern Piedmont, it remained stagnant or declined in other areas, including much of the southern Piedmont (U.S. Census Bureau, 2010). To illustrate the contrasts between the northern Piedmont and the southern Piedmont, two counties—Culpeper County and Pittsylvania County—are described briefly below.

Culpeper County is an exurban area located beyond the suburbs of Washington, D.C. It is a relatively small-sized county, with a land area of 381 square miles and a 2010 population density of 123 people per square mile. Some key characteristics of the county are summarized in Table 2.5, and are contrasted with Pittsylvania County, the city of Danville, and Virginia as a whole. Culpeper County is growing rapidly and prospering economically, with an unemployment rate of 6.4 percent (Table 2.5; see also Figure 2.5). Traditionally rural and agricultural, the county's economy is increasingly based on nonagricultural enterprise. Between 2002 and 2007, the number of farm acres declined 11 percent, and while the number of farms remained stable, the market value of products sold declined by 26 percent.[18] In 2008, over 12,000 employees worked in non-agricultural sectors, with a total annual payroll of nearly $460 billion.[19] Sectors with more than 500 employees included construction; manufacturing; wholesale trade; retail trade; information; professional, scientific, and technical services; health care and social assistance; accommodation and food services; and other, non-public-administration services.

By contrast, Pittsylvania County has a land area of 971 square miles and a 2010 population density of 65 people per square mile (excluding Danville, which is an independent jurisdiction adjacent to Pittsylvania County that for census purposes is treated like a county). The largest county in Virginia, Pittsylvania County is located on the border of North Carolina. Unlike Culpeper County, Pittsylvania County is lagging far behind the state as a whole in population growth and in its economic well-being (Table 2.5). In 2008, fewer than 9,000 employees worked in non-agricultural sectors, with a total annual payroll of just under $233 billion. Sectors with more than 500 employees included construction, manufacturing, retail trade, health care and social assistance, and other non-public-administration services.

Agriculture is a leading economic sector for the county. Between 2002 and 2007, the number of farms in the county increased by 4 percent, and the aver-

[18] http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/County_Profiles/Virginia/index.asp.

[19] http://censtats.census.gov/cgi-bin/cbpnaic/cbpsect.pl.

TABLE 2.5 Culpeper County, Pittsylvania County, Danville, Virginia, and U.S. Population Statistics

Characteristic	Culpeper County	Pittsylvania County	Danville	Virginia	U.S.
Population, 2010 estimate	46,689	63,506	43,055	8,001,024	308,745,538
Population, % change, 2000-2010	+36.3	+2.9	−11.1	+13.0	+9.7
Unemployment rate in October 2011, not seasonally adjusted, %	6.4	7.7	10.7	6.0	8.5
Persons 65 years old and over, 2009, %	11.7	14.7	21.6	12.2	12.9
White persons not Hispanic, 2010, %	71.7	74.4	46.7	64.8	63.7
Black persons, 2010, %	15.8	22.1	48.3	19.4	12.6
Foreign-born persons, 2005-2009, %	6.7	2.3	2.7	10.1	12.4
Bachelor's degree or higher+, 2005-2009, % of persons age 25	21.2	13.0	15.7	33.4	27.5
Median household income, 2009	$61,217	$39,531	$29,466	$59,372	$50,221
Persons below poverty level, 2009, %	9.6	15.6	25.1	10.6	14.3
Adults that currently smoke and report smoking over 100 cigarettes in their lifetime, 2011, %	21	24	25	20	15[a]
Private nonfarm employment, % change, 2000-2008	+23.3	−23.5	−9.0	+9.7	

[a]National benchmark.

SOURCES: Compiled from U.S. Census Bureau, Culpeper County (http://quickfacts.census.gov/qfd/states/51/51047.html; accessed 11 August 2011), Pittsylvania County (http://quickfacts.census.gov/qfd/states/51/51143.html; accessed August 2011), Danville city (http://quickfacts.census.gov/qfd/states/51/51590.html; accessed August 2011), Virginia, and United States (http://quickfacts.census.gov/qfd/states/00000.html), Quick Facts, U.S. Bureau of Labor Statistics (http://www.bls.gov/ro3/valaus.htm; accessed September 2011), and County Health Rankings (http://www.countyhealthrankings.org/virginia; accessed September 2011). All Pittsylvania County data and statistics exclude data for Danville.

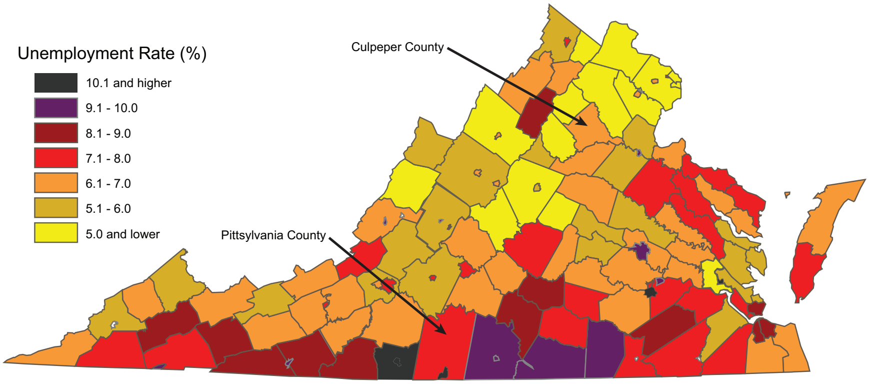

FIGURE 2.5 **Unemployment rate in Virginia for July 2011. The overall rate of unemploy-**ment (not seasonally adjusted) for the state was 6.2 percent. Danville is the small black area mostly enclosed by Pittsylvania County. SOURCE: U.S. Bureau of Labor Statistics (http://www.bls.gov/ro3/valaus.htm; accessed September 2011).

age market value of products sold increased by 10 percent,[20] despite a 5 percent decline in the total acreage of farmland. The county's key agricultural products include livestock and grain as well as various fruits and vegetables. Tobacco remains a key agricultural product and also brings in revenue from the federal government. In 2007, Pittsylvania County was the top-ranked Virginia county for tobacco production (USDA, 2009). Between 2000 and 2010, Pittsylvania County received $16M in federal tobacco subsidies, approximately $10M of which was in the form of tobacco transition payments.[21] These payments began in 2004 as a method to end tobacco quotas (P.L. 108-357), and are due to end in 2014. In addition to federal tobacco subsidies, Pittsylvania County and the city of Danville received grants from the Virginia Tobacco Indemnification and Community Revitalization Commission to promote economic growth and education in tobacco-dependent regions (VTICRC, 2010). Between 1995 and 2010, the county received an additional $21.5M for disaster payments, wheat subsidies, corn subsidies, and payments from the Conservation Reserve Program.[22] In 2010, Pittsylvania County was the 2nd ranked county in Virginia for U.S. Department of Agriculture subsidies,[23] and was ranked seventh in the state for the period 1995-2010.[24]

[20]http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/County_Profiles/Virginia/index.asp; accessed April 2011.

[21]http://farm.ewg.org/progdetail.php?fips=51143&progcode=tobacco.

[22]http://farm.ewg.org/region.php?fips=51000.

[23]http://farm.ewg.org/progdetail.php?fips=51000&progcode=total&page=county&yr=2010&regionname=Virginia.

[24]http://farm.ewg.org/progdetail.php?fips=51000&progcode=total&page=county&regionname=Virginia.

Although not officially part of Pittsylvania County, Danville—on the county's southern border—is its largest proximate city. The population size and economy of Danville have been even more stagnant than those of Pittsylvania County, having experienced two decades of declining growth (−11.1 percent from 2000 to 2010, and −8.7 percent from 1990 to 2000),[25] and with a current unemployment rate of 10.7 percent (Table 2.5). Danville's two main industries have historically been tobacco and textiles, which by the 1980s were no longer competitive with manufacture in others parts of the world (Johnson et al., 2010).

FINDINGS AND KEY CONCEPTS

The committee's analysis of the physical and social context within which uranium mining and processing might occur has produced the following findings:

- ***Virginia has a diverse natural and cultural heritage.*** Each of the five physiographic provinces—the Appalachian Plateau, Valley and Ridge, Blue Ridge Mountains, Piedmont, and Coastal Plain—has distinct geological, climatic, ecological, agricultural, and cultural characteristics, as do subregions within each province. To protect Virginia's valued resources, a detailed assessment of both the potential site and its surrounding area (including natural, historical, and social characteristics) would be needed if uranium mining and processing were to be undertaken. Virginia's natural resources include a wide range of plants, animals, and ecosystems, a large number of which are currently under significant stress.
- ***Statewide demographic statistics mask significant socioeconomic disparities within Virginia.*** Although the statewide demographic statistics for Virginia are similar to those for the entire United States, the demographic makeup of the state varies greatly, both among and within its physiographic provinces. A comparison of Culpeper and Pittsylvania counties, in the northern and southern Piedmont, respectively, reveals that Pittsylvania County has a much lower education, household income, and population growth profile, with much higher rates of poverty and smoking. Pittsylvania County is currently the most likely possibility to host a uranium mining and processing operation, based on the location of known uranium deposits (see Chapter 3).
- ***Virginia is subject to extreme natural events, including relatively large precipitation events and earthquakes.*** Virginia has a positive water balance (a wet climate with medium to high rainfall), and is subject to extreme precipitation events associated with convection, frontal activity, tropical storms, and hurricanes, with the potential to result in record flood discharges, debris flows and avalanches, landslides, extensive property damage, and loss of life. In addition, parts of Virginia do have some seismic risk, and the state experienced a 5.8-magnitude

[25] http://factfinder.census.gov/servlet/QTTable?_bm=n&_lang=en&qr_name=DEC_1990_STF1_DP1&ds_name=DEC_1990_STF1_&geo_id=05000US51590.

earthquake in 2011. Although very difficult to accurately forecast, the risks and hazards associated with extreme natural events would need to be taken into account when evaluating any particular site's suitability for uranium mining and processing operations.

3

Uranium Occurrences, Resources, and Markets

Key Points

- Of the localities in Virginia where existing exploration data indicate that there are significant uranium occurrences, predominantly in the Blue Ridge and Piedmont geological terrains, only the deposits at Coles Hill in Pittsylvania County appear to be potentially economically viable at present.
- Because of their geological characteristics, none of the known uranium occurrences in Virginia would be suitable for the in situ leaching/in situ recovery (ISL/ISR) uranium mining/processing technique.
- In 2008, uranium was produced in 20 countries; however, more than 92 percent of the world's uranium production came from only eight countries.
- In general, uranium price trends since the early 1980s have closely tracked oil price trends. The Chernobyl (Ukraine) nuclear accident in 1986 did not have a significant impact on uranium prices, and it is too early to know the long-term uranium demand and price effects of the Fukushima (Japan) accident.
- Existing known identified resources of uranium worldwide, based on present-day reactor technologies and assuming that the resources are developed, are sufficient to last for more than 50 years at today's rate of usage.

This chapter contains a brief description of the wide variety of geological settings that host uranium deposits worldwide, and then a more specific description of known uranium occurrences in the Commonwealth of Virginia. This latter section also notes the exploration status and a first-order indication of the exploitation potential of existing uranium resources in Virginia. The final section in this chapter describes uranium resource and reserve concepts, and reviews global and national uranium market trends.

WORLDWIDE OCCURRENCES OF URANIUM

Uranium deposits are known to occur as a result of a wide range of processes, from magmatic and fluid fractionation deep in continental crust to evaporation at the Earth's surface (Box 3.1; Figure 3.2). The resulting concentrations of uranium within different rock types have an equally broad range, from a fraction of a part per million in ultramafic rocks up to 76 ppm in phosphorites (Lassetter, 2010; see Table 3.1). Uranium deposits have been mined with the most extreme range of grade (from about 1×10^2 grams/tonne of uranium for the phosphates of Florida, to nearly 2×10^5 grams/tonne of uranium in the unconformity-related McArthur River deposit in Canada) and tonnage (from a few tonnes for some intragranitic veins in the French Massif Central to nearly 2 million tonnes of uranium (tU) in Australia's Olympic Dam deposit).

IAEA Classification of Uranium Deposits

The International Atomic Energy Agency (IAEA) has classified uranium resources—on the basis of their geological setting and morphology—into a number of ore deposit types (IAEA, 2009). These are presented here in order of their approximate global economic significance:

Unconformity-Related Deposits

These deposits are spatially related to an unconformable contact separating crystalline basement from an overlying thick siliciclastic sediment sequence, with the deposits occurring at the contact level, and/or below or above the contact. Two subtypes of unconformity-related deposits are recognized (IAEA, 2009):

- Fracture controlled, dominantly basement-hosted deposits (e.g., McArthur River, Rabbit Lake, and Eagle Point in Canada; Jabiluka, Ranger, Nabarlek, and Koongarra in Australia)
- Clay bounded, massive ore developed along and just above, or immediately below, the unconformity in the overlying cover sandstones (e.g., Cigar Lake and Key Lake in Canada)

BOX 3.1
Chemical and Physical Properties of Uranium and Geological Processes

Uranium is the heaviest and last naturally occurring element in the periodic table, with an atomic number of 92 and an atomic mass of 238. Because of its large ionic radius and high charge, uranium does not enter in the structure of major rock-forming minerals, and consequently is continuously enriched in melts either during magmatic processes such as partial melting or fractional crystallization. As a result, the most fractionated magmas—which are generally the richest in silica—are the most enriched in uranium; granites and rhyolites are much richer in uranium than mafic igneous rocks such as basalts or gabbros. In igneous rocks, uranium is associated with enriched thorium (Th), zirconium (Zr), titanium (Ti), niobium (Nb), tantalum (Ta), and rare earth elements (in minerals such as zircon, apatite, monazite, titanite, allanite, uraninite, etc.), particularly in peralkaline rocks but less so for metaluminous rocks and much less for peraluminous rocks.

Levels of uranium in common sedimentary rocks are closely related to the oxidation-reduction conditions. The highest concentrations (tens to hundreds of parts per million [ppm][a]) are found in sediments that are rich in organic matter or phosphate. Lower uranium contents are generally recorded in coarse-grained sediments, and higher values in clay-rich sediments.

Uranium in nature occurs in two main oxidation states, U^{4+} and U^{6+}. The U^{4+} state is stable in reducing conditions, weakly soluble in most geological conditions, and is the main valence occurring in uranium ore minerals (dominantly tetravalent uranium minerals). U^{6+} forms the uranyl UO_2^{2+} species, which is stable in oxidizing conditions and forms a large series of complexes (hydroxides, carbonates, sulfates, phosphates, etc.) which are very soluble in geological fluids. The uranyl species enters into the structure of hexavalent uranium minerals, which are also called secondary uranium minerals because they commonly result from the oxidation of tetravalent uranium minerals by interaction with oxygen-bearing surficial waters.

Uranium minerals are extremely diverse. Approximately 5 percent of all known minerals contain uranium as an essential structural constituent (Burns, 1999), although many of the hundreds of uranium-bearing minerals are rarely encountered mineral "curiosities." Among the tetravalent uranium minerals, the two principal ones occurring in ore deposits are uraninite, with a UO_{2+x} composition (called pitchblende when occurring with a colloform texture), and coffinite ($USiO_4$).

Other common tetravalent minerals that generally contain several percent to several tens of percent of uranium are uranothorite $(Th,U)SiO_4$, brannerite $(U,Ca,Ce)(Ti,Fe)_2O_6$, ningyoite $(U,Ca,Ce)_2(PO_4)_2 \cdot 1.5H_2O$, Nb-Ta-Ti minerals such as uranmicrolite $(U,Ca,Ce)_2(Nb,Ta)_2O_6(OH,F)$, uranpyrochlore $(U,Ca,Ce)_2(Ta,Nb)_2O_6(OH,F)$, euxenite $(Y, Er, Ce, La, U)(Nb, Ti, Ta)_2(O,OH)_6$, and can be also associated with organic matter in thucolite. Hexavalent uranium minerals are less abundant in ore deposits, but are the most diverse. They are highly colored and can be deposited either as primary ore minerals such as carnotite $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$, tyuyamunite $Ca(UO_2)_2(VO_4)_2 \cdot 3H_2O$, or more commonly as alteration products of tetravalent uranium minerals such as autunite $Ca(UO_2)_2(PO_4)_2 \cdot 10H_2O$ or uranophane $Ca(UO_2)_2SiO_3(OH)_2 \cdot 5H_2O$.

Uranium also occurs as a minor constituent in accessory minerals such as zircon $(Zr,U)SiO_4$, monazite $(LREE,Th,U)PO_4$, xenotime $(Y,HREE,U)\ PO_4$, bastnaesite $(LREE)CO_3F$, and others. More comprenhensive information about uranium minerals is provided in Burns (1999), Finch and Murakami (1999), and Krivovichev et al. (2006).

Aqueous Geochemistry of Uranium

Uraninite and most other common uranium minerals are only sparingly soluble in water at neutral pH, low temperatures, and reducing conditions. The solubility of uraninite increases markedly in oxidizing conditions in the presence of anions such as OH^-, F^-, Cl^-, CO_3^{2-} SO_4^{2-}, and PO_4^{3-}, which form strong complexes with UO_2^{2+} (e.g., Langmuir, 1978; Guillaumont et al., 2003). These complexes considerably enhance the mobility of uranium in groundwater. For example, uranium is readily soluble in the strongly acidic, oxidizing water commonly associated with acid mine drainage because UO_2^{2+} sulfate complexes are stable below pH 4 (for a recent review of available data, see Kyser and Cuney, 2008). In oxidized fluids between pH 4 and 7.5, uranyl phosphate complexes become the important species with concentrations of only 0.1 ppm PO_4. At higher pH, uranyl hydroxide or uranyl carbonate complexes predominate. As a result, sulfuric acid with pH of about 1 is used for in situ recovery in roll-front-type deposits (e.g., in Kazakhstan) and sodium carbonate solutions with an oxidant are used for in situ leaching of uranium in sandstone deposits in the Unites States. In reduced groundwater, at very low pH, only fluoride complexes of U^{4+} are significant; only at very high pH are uranyl hydroxides the dominant species, whereas at intermediate pH (between 4 and 8) uraninite solubility is extremely low (Langmuir, 1978).

Eh-pH[a] diagrams are a convenient way of visually summarizing the dominant aqueous speciation and mineralogy of redox-sensitive elements, such as uranium. The diagrams are constructed in a systematic way using a defined set of assumptions, initial conditions, chemical reactions for the system of interest, and the accompanying thermodynamic data. The final diagram depends on all of these factors; therefore, a very large number of Eh-pH diagrams could be constructed for uranium alone. They only depict equilibrium relationships, and the user must bear in mind that natural waters are commonly not at equilibrium. Nevertheless, these diagrams are a useful and enduring tool in the study and interpretation of natural waters.

A generic example of an Eh-pH diagram for the $U–O_2–H_2O–CO_2$ system at 25°C is shown in Figure 3.1, assuming $P_{CO_2} = 10^{-3.5}$ atm (equilibrium with atmospheric CO_2) and the median major ion composition of groundwater (Table 8.8 in Langmuir, 1997). The thermodynamic data were from the extensive reviews of Grenthe et al. (1992) and Guillaumont et al. (2003). Fields represent the range of Eh and pH conditions where each form dominates, that is, constitutes more than 50 percent of the uranium in the system, but neighboring forms will also be present. The boundaries separating the fields indicate where neighboring forms are present at equal concentration (strictly speaking, equal activity). The diagonal dashed lines at the top and bottom of the figure delineate the stability field of liquid water as a function of Eh and pH. In the large blue field in the upper left, the uranyl cation (UO_2^{2+})

continued

BOX 3.1 Continued

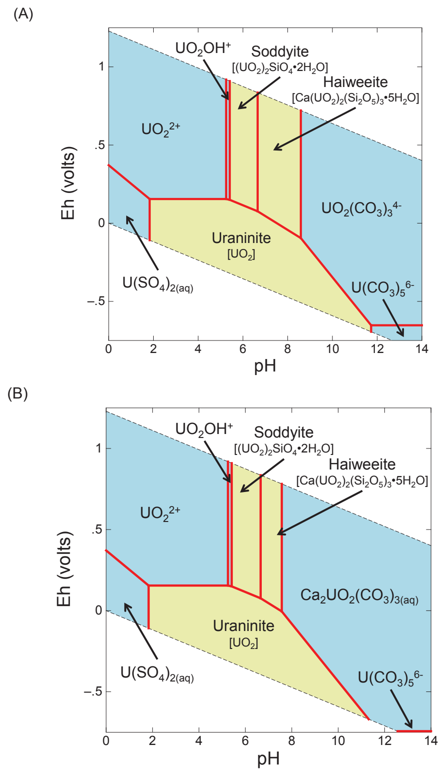

FIGURE 3.1 Eh-pH diagram for the $U–O_2–H_2O–CO_2$ system at 25°C assuming $P_{CO_2} = 10^{-3.5}$ atm (equilibrium with atmospheric CO_2) and the median major ion composition of groundwater (Table 8.8 in Langmuir, 1997). The fields shaded blue represent species dissolved in water (aqueous species) while the fields shaded tan represent solid mineral phases. The diagonal dashed lines at the top and bottom of the figure delineate the stability field of liquid water. Thermodynamic data are from Grenthe et al. (1992) and Guillaumont et al. (2003). $U^{IV}–S^{II}$ species were not considered in this diagram. SOURCE: Committee-generated using The Geochemist's Workbench® (Bethke, 2010).

would dominate uranium speciation at equilibrium. In that same field, some of the hydrolysis product UO_2OH^+ would also be present, but at lower concentrations than UO_2^{2+}. Uraninite, a poorly soluble mineral of tetravalent—or reduced—uranium, occupies the large tan stability field at the bottom center of the diagram.

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[a]Eh represents the oxidation-reduction potential of a solution.

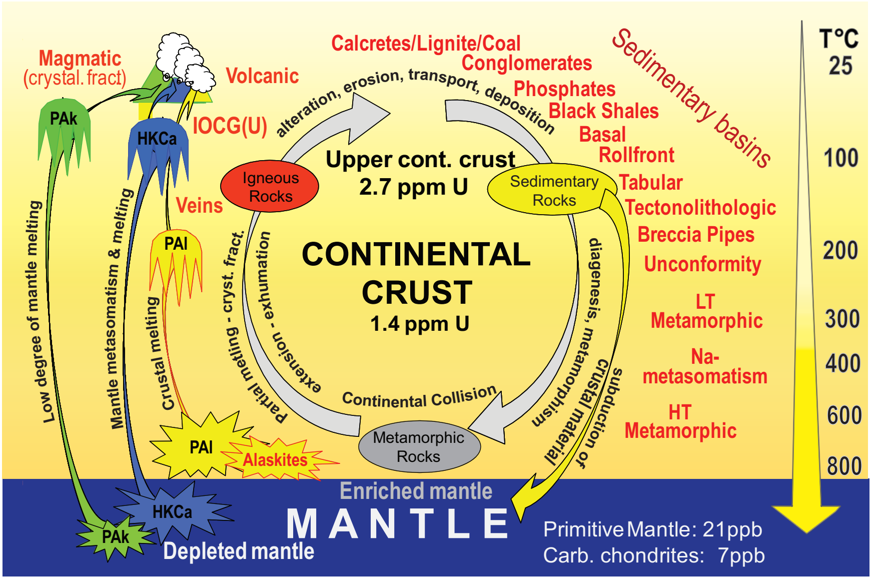

FIGURE 3.2 Schematic diagram illustrating the very wide range of geological processes that have resulted in uranium deposits. Average uranium concentrations of the main uranium reservoirs—the mantle (in blue), the crust (in yellow), and the upper crust are given. The circular arrows indicate the evolution of the geological cycle from surficial processes (alteration, erosion, transport by river and deposition) that produce sedimentary rocks, to deeper processes (burial of sedimentary rocks with increasing temperature and pressure) that produce metamorphic rocks; some of these rocks may be injected into the mantle during subduction. Increasing temperature leads to melting of the rocks in the continental crust and/or in the mantle and the genesis of plutonic and volcanic rocks that are injected in the Earth's crust. Three main types of magmas can be enriched in uranium: PAl: peraluminous magmas resulting from the partial melting of sedimentary rocks (PAl); highly potassic calc-alkaline magmas resulting from the partial melting of a mantle contaminated by subducted sediments (HKCa); and peralkaline magma resulting from very low degree of partial melting of a mantle, which can be contaminated (Pak). The main message in the schematic is the extreme variability of possible host rocks and concentration processes that can lead to potentially exploitable uranium deposits. SOURCE: Modified from Cuney (2009).

TABLE 3.1 Global Averaged Uranium and Thorium in Different Rock Types

Rock Type	Uranium Content (ppm)	Thorium Content (ppm)	Thorium/Uranium Ratio
Ultramafic	0.01	0.05	3.6
Basalt	0.4	1.6	4.0
Gabbro	0.8	3.8	4.7
Granite	4.8	21.5	4.5
Nepheline syenite	14	48	3.4
Granulite	1.6	7.2	4.5
Granitic gneiss	3.5	12.9	3.7
Sandstone	1.4	5.5	3.9
Shale	3.2	11.7	3.7
Carbonate	2.2	1.2	0.5
Carbonaceous shale	8.0	1.7	0.2
Marine phosphorite	76		<1
Upper Crust Average	2.5	10	4
Seawater	0.003	10^{-5}	0.0002

SOURCE: Modified from Lassetter (2010); compiled from Rogers and Adams (1969), Woodmansee (1975), Gabelman (1977), and Rose et al. (1979).

These are the highest grade deposits in the world (generally higher than 1 percent uranium, and up to 20 percent for the McArthur River deposit). Their tonnages vary from some thousands of tonnes of uranium (tU) to more than 200,000 tU.

Sandstone Deposits

These deposits occur in medium- to coarse-grained sandstones deposited in continental fluvial or marginal marine sedimentary environments. The uranium is precipitated under reducing conditions associated with carbonaceous material, and/or sulfides, and/or hydrocarbons, and/or iron-magnesium minerals, disseminated within the sandstone. Four main subtypes are distinguished:

- ***Roll-front deposits***. Uranium mineralized zones are crescent-shaped in cross section, sinuous horizontally, and localized between reduced sandstone on the hydrological gradient downside and oxidized sandstone on the hydrological gradient upside. Resources range from a few hundred tonnes to several tens of thousands of tonnes of uranium, at grades from 0.015 percent to 0.25 percent. Examples are Moynkum, Inkay, and Mynkuduk in Kazakhstan; and Crow Butte and Smith Ranch in the United States.
- ***Tabular deposits***. Uranium minerals impregnate the sandstone matrix within tabular, irregularly shaped, lenticular masses within reduced sediments.

Individual deposits contain several hundreds of tonnes up to 200,000 tonnes of uranium, at average grades ranging from 0.05 percent to 0.5 percent, and occasionally up to 1 percent. Examples of such deposits include the Colorado Plateau in the United States; and Akouta, Arlit, and Imouraren in Niger.

- ***Basal channel deposits (paleovalleys)***. Uranium minerals are deposited within permeable alluvial-fluvial sediments that fill channels incised into uranium-rich basement granites, and generally sealed by basalt flows. Individual deposits can range from several hundreds to 20,000 tonnes of uranium, at grades ranging from 0.01 percent to 3 percent. Examples are the deposits of Dalmatovskoye (Transural Region) and Khiagdinskoye (Vitim district) in Russia.
- ***Tectonic/lithologic deposits***. Uranium mineral precipitation is controlled both by the lithology and by tectonic structures. Individual deposits contain a few hundreds to 5,000 tonnes of uranium at grades of 0.1 percent to 0.5 percent. An example is the deposit of Mas Laveyre in France.

Hematite Breccia Complex Deposits

These deposits occur in hematite-rich breccias, where the uranium minerals are associated with copper, gold, silver, and rare earths. The only representative of this type of deposit presently being mined is Olympic Dam in South Australia. This is the largest mined uranium deposit in the world, with reasonably assured resources (defined below) recoverable at less than US$80/kg U of more than 1.2 million tU (GA/ABARE, 2010).

Quartz Pebble Conglomerate Deposits

Detrital uraninite is deposited, together with pyrite and gold, in monomictic (only quartz pebbles) conglomerates that are the basal units of fluvial to lacustrine braided stream systems older than 2.4 Ga. Examples include the Witwatersrand Basin in South Africa, where uranium is mined as a byproduct of gold (0.02 to 0.05 percent uranium grade), and the Blind River/Elliot Lake area in Canada which has higher grades (0.1 to 0.15 percent uranium), where only uranium was mined.

Vein Deposits (Granite-Related Deposits)

The major component of the mineralization fills fractures associated with strike-slip extension. The veins consist of gangue material (e.g., carbonates, quartz) and uranium minerals. Typical examples range from pitchblende veins (e.g., Pribram in the Czech Republic, Schlema-Alberoda in Germany), to stockworks and episyenite columns (e.g., Bernardan in France), to narrow cracks in granite or metamorphic rocks (e.g., Mina Fe in Spain, Singhbhum in India). Individual deposits contain from a few hundreds of tonnes to 80,000 tonnes of uranium at grades of 0.05 percent to 0.6 percent.

Intrusive Deposits

These deposits are associated with intrusive or anatectic rocks (alaskite, granite, monzonite, peralkaline syenite, carbonatite, and pegmatite). Examples include the Rossing alaskites in Namibia, very-low-grade uranium as a byproduct of porphyry copper deposit mining (such as Bingham Canyon in the United States), the Ilímaussaq lujavrites in Greenland, and the Palabora carbonatite in South Africa.

Volcanic- and Caldera-Related Deposits

These deposits are associated with volcanic caldera that are infilled with mafic to felsic volcanic complexes and intercalated clastic sediments. Mineralization is largely structural-controlled (minor stratabound), occurs at several stratigraphic levels of the volcanic and sedimentary units, and extends into the basement where it is found in fractured granite and in metamorphic rocks. Uranium minerals are commonly associated with molybdenite and fluorite. Individual deposits contain from a few hundreds of tonnes to 37,000 tonnes of uranium at grades of 0.1 percent to 0.3 percent. The most significant deposits of this type are located in Russia (Streltsovska district), China (Xiangshan), and Mongolia (Dornot).

Metasomatic Deposits

The largest deposits of this type occur in Precambrian shields, where they are related to crustal-scale shear zones along which different types of basement rocks—granites, migmatites, gneisses, and banded iron formations—are desilicified and subject to sodium-metasomatism with production of albitites, aegirinites, and carbonaceous-ferruginous rocks. Ore lenses and stocks are a few meters to tens of meters thick, and some are hundreds of meters long. The vertical extent of ore mineralization, mostly brannerite and uraninite, can be more than 1.5 km. Individual deposits contain from a few hundreds of tonnes to 80,000 tonnes of uranium at grades of 0.08 percent to 0.3 percent. Examples include the Michurinskoye and Zheltorechenskoye deposits in Ukraine, and Lagoa Real and Itataia in Brazil.

Surficial Deposits

Surficial uranium deposits result from young (Tertiary to Recent) near-surface uranium mineral deposition in sediments and soils. The largest deposits are paleovalleys filled with poorly sorted siliciclastic rocks in which calcretes (carbonate concretions) are formed in arid to semiarid climatic conditions as a result of evaporation. Individual deposits contain from a few hundreds of tonnes

to 65,000 tonnes of uranium at grades of 0.012 percent to 0.13 percent. The main deposits are in Australia (Yeelirrie) and Namibia (Langer Heinrich and Trekopjje). Surficial uranium deposits also can occur in peat bogs and soils.

Collapse Breccia Pipe Deposits

The breccia pipes are vertical, circular, and result from karst limestone dissolution; they are infilled with fragments derived from the gravitational collapse of overlying formations. The uranium minerals occur in the permeable breccia matrix and in the arcuate, ring-fracture zone surrounding the pipe. Individual deposits contain from a few hundreds of tonnes to a few thousands of tonnes of uranium at grades of 0.16 percent to 0.85 percent. Type examples are the deposits in the "Arizona Strip" north of the Grand Canyon.

Phosphorite Deposits

These deposits consist of synsedimentary stratiform marine phosphorites deposited on the continental shelf. The uranium is hosted by apatite, and can be recovered as a byproduct of phosphoric acid production. Phosphorite deposits constitute large uranium resources, but at a very low grade. Individual deposits contain from tens of thousands of tonnes to more than 3 million tonnes of uranium at grades of 0.01 percent to 0.03 percent. Examples include the pebble phosphate deposit of New Wales in Florida, and Gantour in Morocco. Some phosphorite deposits consist of argillaceous marine sediments rich in uraniferous fish remains (e.g., Melovoe in Kazakhstan).

Other Deposits

The following deposits are of lesser importance

- ***Metamorphic deposits***. The concentration of uranium directly results from metamorphic processes. The age of uranium deposition and the temperature and pressure at which it occurred are similar to those of the enclosing rocks. Examples include the Forstau deposit in Austria and the Mary Kathleen deposit in Australia.
- ***Limestone and paleokarst deposits***. An example includes uranium mineralization in the Jurassic Todilto Limestone in the Grants district of New Mexico, where uranium oxides occur in intraformational folds and fractures.
- ***Coal deposits.*** Elevated uranium contents occur in lignite/coal and in clay and sandstone immediately adjacent to lignite/coal. Examples are the Serres Basin in Greece, and occurrences in North Dakota. Uranium grades are very low, averaging less than 50 ppm of uranium.

Rock Types with Elevated Uranium Contents

Rock types with elevated uranium content include granites and black shales. No deposits have been mined commercially in these types of rocks; grades are very low, and it is unlikely that these types of uranium accumulations would become economic in the foreseeable future on their own, although uranium can be extracted as a byproduct if other associated elements reach economic concentrations (see below).

"Unconventional" Uranium Deposits

The IAEA has defined uranium "unconventional resources" as resources from which uranium can only be recovered as a minor byproduct, such as the uranium associated with phosphorites, nonferrous ores, carbonatites, black shales, lignite, and seawater. However, this definition may evolve depending on uranium prices and technological improvements, and some of these resources—such uranium in black shales or phosphorites—may become a significant resource in the future.

Other major nonconventional resources are the following:

- Several projects are being developed (many in South Africa, and also in the Czech Republic, Kyrgyzstan, and Tajikistan) for reprocessing the tailings produced during previous uranium or other metal extraction. For example, Rand Uranium is currently determining the feasibility of reprocessing tailings to extract gold and uranium in the Randfontein/Westonaria region, Witwatersrand, South Africa.
- About 1,100 tU have been recovered from lignite ash produced from 1964 to 1967 in North Dakota. In China, there is testing of uranium extraction from coal ash produced by the burning of lignite coal.
- Uranium may be extracted from monazite recovered from sand placers, if rare earth elements (REE) and thorium production from this resource restart in the future. Monazite from sand placers typically contains several thousand parts per million of uranium.
- Uranium has been recovered from porphyry copper operations in the United States and Chile that have very low uranium grade (tens of parts per million), and it is likely that other ore deposits that are presently being mined also contain significant levels of uranium. Recently, the Talvivaara nickel-zinc mine in Finland, with 15-20 ppm uranium in the ore, announced production of about 350 tU per year from the leach solution.
- Tens of tonnes of uranium are produced each year from water treatment processes associated with the management of former uranium mines and tailings.

Classification of Uranium Deposits Based on Ore Formation Processes

Although there have been a number of classifications published for uranium deposits (e.g., Dahlkamp, 1993, 2009), the IAEA classification described above is the most commonly used, based principally on the nature of the enclosing rocks and the morphology of the uranium deposits. One disadvantage of the IAEA classification is that deposits resulting from very different genetic processes and occurring in very different geological environments can end up being grouped in the same category, and this is especially true for vein deposits and uranium deposits disseminated in plutonic rocks. In the case of plutonic rocks, this category contains deposits resulting from partial melting in deep structural settings within high grade metamorphic rocks (e.g., the alaskite dykes of Rössing, in Namibia), as well as deposits resulting from extreme fractional crystallization occurring in very surficial settings at the apex of peralkaline complexes (e.g., the Ilímausaq peralkaline complex in Kvanfjeld, Greenland).

During the past 60 years, there has been tremendous progress in knowledge concerning the physical and chemical processes controlling the formation of uranium deposits, and it is now possible to classify uranium deposits based on their genesis, mainly reflecting differences in the physical and chemical fractionation processes acting during different stages of the geological cycle (Cuney and Kyser, 2008; Cuney, 2010). In comparison to other metals, scientific knowledge of uranium fractionation mechanisms is uniquely helped by its natural radioactive properties. These allow abundance to be estimated from the smallest scale, at less than the part-per-million level using fission tracks analyses, to the crustal scale using heat flow/heat production relations. In addition, uranium accumulation can be dated directly using geochronometers ($^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$) for million to billion year timescales, or by using isotopes from the decay chain of the two uranium isotopes for timescales less than a million years.

The metal accumulation in a given ore deposit depends on the combined efficiency of the successive fractionation processes that occurred, including metal extraction from the source, metal transport, and metal deposition. Each of these processes is represented in the following genetic classification of uranium deposits, based on the most effective metal concentration mechanism in a given deposit, and is used below in the description of potential uranium deposits in Virginia:

1—Fractional crystallization, for example, Ilímausacq in Greenland, Bokan Mountain in Alaska. Corresponds to part of the IAEA's intrusive type of deposits, but is always associated with the most extremely fractionated magmas in peralkaline magmatic association. They are located at very high levels in continental crust.

2—Partial melting, for example, Rössing in Namibia. Also corresponds to part of the IAEA's intrusive type of deposits, but in this case results from the partial melting of uranium-rich sediments deep in continental crust.

3—Hydrothermal high-level post-orogenic. Corresponds mostly to the IAEA's vein-type deposits, but here is classified as deposits resulting from the circulation of hot fluids at high levels in continental crust (either in volcanic or plutonic rocks), and occurring after the formation of a mountain belt (post orogenic).

3A—Volcanic–hydrothermal, for example, Streltsovska in Russia. Equivalent to the IAEA's volcanic- and caldera-related deposits; results from hot fluid circulation in volcanic rocks.

3B—Granitic–hydrothermal, for example, French Variscan, Erzgebirge in southeastern Germany and the Czech Republic. Equivalent to the IAEA's vein-type deposits (granite-related deposits); results from hot fluid circulation in plutonic rocks.

4—Diagenetic hydrothermal systems. Corresponds to many of the IAEA deposit types, but all are generated by the circulation of hot brines (highly saline solutions) circulating in more or less buried sedimentary basins. Three main subtypes are distinguished according to the location of the reduction-oxidation (redox) boundary that controls uranium deposition:

4A—Basin/basement redox control (IAEA's unconformity-related deposit); the redox boundary is located at the base of the sedimentary basin.

4B—Interformational redox control, for example, Oklo, Gabon (included in the IAEA's sandstone type); the redox boundary is located between two formations within the sedimentary basin.

4C—Intraformational redox control; the redox boundary is located within a permeable sedimentary formation; these are divided into three subtypes according to their morphology:

4C1—Tabular, for example, Grants Mineral Belt in the United States, Beverly in Australia (same as the IAEA classification)

4C2—Tectonolithologic, for example, Akouta, Niger (same as the IAEA classification)

4C3—Karsts (breccia pipes), for example, Colorado in the United States (collapse breccias pipes in the IAEA classification)

5—Hydrothermal metamorphic, for example, Shinkolobwe in the Democratic Republic of Congo, Mistamisk in Quebec, Canada (IAEA's metamorphic deposits); resulting from the circulation of metamorphic fluids.

6—Hydrothermal metasomatic (IAEA's metasomatite deposits):

6A—Alkali-metasomatism, for example, Lagoa Real in Brazil, Krivoi Rog in Ukraine; resulting from regional-scale circulation of fluids of unknown origin, with dissolution of quartz and replacement of most other minerals by albite.

6B—Skarns, for example, Mary Kathleen in Australia, Tranomaro in Madagascar; resulting from fluid and element exchange between a granitic magma and enclosing marbles.

7—Synsedimentary (corresponds to a range of IAEA deposit types); deposits resulting from uranium concentration occurring simultaneously with deposi-

tion of the sediment that formed the sedimentary rock, although by different processes:

7A—Mechanical sorting: quartz pebble conglomerates, for example, Witwatersrand, Elliot Lake (IAEA quartz pebble conglomerates); uranium concentration results from a purely physical (mechanical) process.

7B—Redox trapping: black shales, for example, alum shales, Sweden (marine and continental) (IAEA black shale unconventional deposits), resulting from the reduction of uranium contained in sea or lake water by the organic matter deposited with the shales.

7C—Crystal-chemical/redox trapping, phosphates, for example, Maroc (IAEA phosphorite deposits); uranium from seawater is incorporated into the crystal structure of apatite in reducing conditions. Apatite is the main component of fish bones that are locally accumulated on epicontinental platforms under favorable conditions.

8—Intraformational meteoric fluid infiltration, deposits formed by the infiltration of meteoric water at low temperature in permeable sedimentary rocks:

8A—Along sealed paleovalleys, for example, Vitim in Transbaikalia (IAEA's basal channel deposits)

8B—As roll fronts, for example, Powder River Basin in Wyoming (IAEA's roll-front deposits)

9—Weathering and evaporation, calcretes, for example, Yeleerie in Australia (IAEA's surfical deposits; more specifically calcretes)

10—Other types, breccia complex, for example, Olympic Dam in Australia (IAEA's hematite breccia complex), here classified as "other" because the conditions of formation are insufficiently known for precise classification.

VIRGINIA OCCURRENCES AND PROSPECTIVITY STATUS

Lassetter (2010) recently presented a compilation of uranium occurrences in the Commonwealth of Virginia, using published reports, unpublished geochemical data, and field scintillometer measurements, and this compilation forms much of the basis for this section. More than 55 uranium occurrences were identified by Lassetter (2010) (Figure 3.3), based on the presence of uranium-bearing minerals, the detection of elevated natural radioactivity, and/or geochemical data indicating elevated uranium content when compared with the expected natural background concentrations. These occurrences represent uranium concentrations in seven of Virginia's geological terrains (Lassetter, 2010): (1) Tertiary-age marine phosphatic sedimentary rocks, (2) Late Jurassic–Early Cretaceous alkalic igneous rocks, (3) Triassic-Jurassic carbonaceous sedimentary strata and contact metamorphic aureoles, (4) Late Paleozoic pegmatites and late magmatic-stage granitic rocks, (5) Late Devonian and Early Mississippian black shales and sandstones, (6) Middle and Late Proterozoic alkali-rich plutonic rocks, and (7) major cataclasite/mylonite zones.

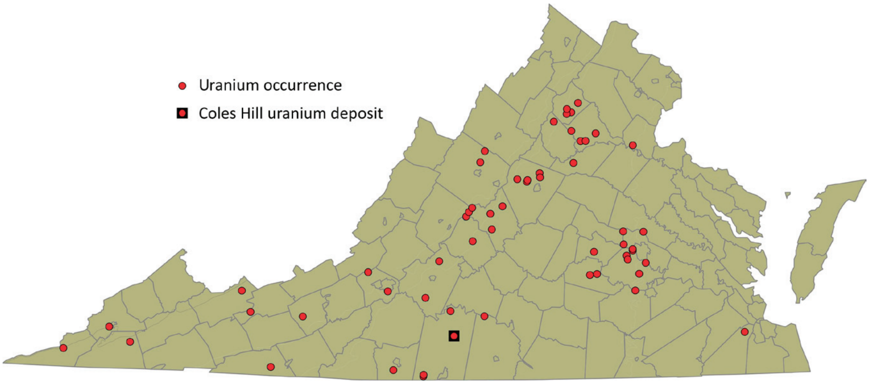

FIGURE 3.3 Map showing uranium occurrences in Virginia; subsequent figures present this information for each of the different types of uranium occurrence. Note that uranium occurrences are not necessarily uranium ore deposits. SOURCE: Modified from Lassetter (2010).

In the mid to late 1970s, the U.S. government took steps to stimulate uranium exploration in response to the 1973 OPEC oil embargo. The National Uranium Resource Evaluation (NURE) program was created with the goal of identifying uranium resources in the United States (Smith, 2006). One of the main components of this program was an airborne gamma-ray spectrometry survey to detect gamma-ray emissions from radioactive decay of uranium (U), thorium (Th), and potassium (K) (Duval et al., 2005). The NURE maps indicate varying levels of surface concentrations of U, Th, and K (Kucks, 2005; see Figure 3.4). In 1977, Marline Uranium Corporation initiated ground surveys in Virginia in search of uranium deposits, and began to acquire mineral leases in Pittsylvania, Fauquier, Orange, Madison, and Culpeper counties. In 1982, Marline announced the discovery of orebodies and formed a joint venture with Union Carbide Corporation to develop the South deposit at what is now called Coles Hill (Reynolds, 2010). That same year, the Virginia legislature instituted a statewide moratorium on uranium mining but left available the right to explore for uranium. In 2007, Virginia Uranium Inc. applied for and received an exploration permit to drill new exploratory drill holes in and around the Coles Hill.

Uranium deposits that are presently known in Virginia, or may potentially occur based on lithological characteristics, are described together with an estimate of discovery and mining potential for the foreseeable future. These are presented according to the deposit types based on genesis presented above, because this type of classification is better suited for predicting the occurrence of uranium deposits in poorly explored areas.

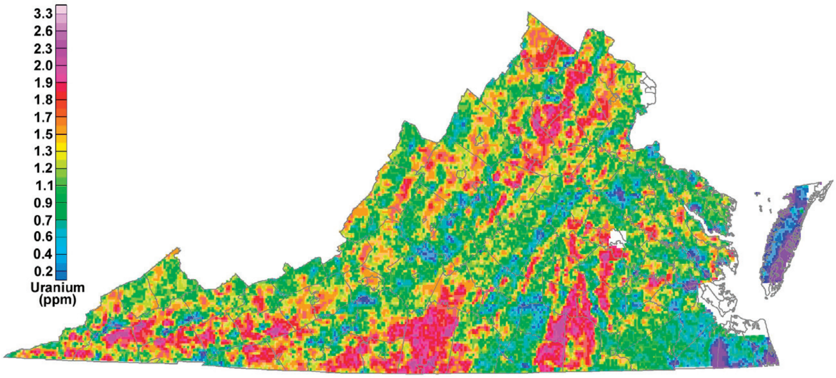

FIGURE 3.4 Aeroradiometric map of Virginia showing the concentration of uranium (eU) in the top few centimeters of rock or soil, derived by reprocessing National Uranium Resource Evaluation (NURE) program aerial gamma-ray data. SOURCE: Kucks (2005).

Granitic Hydrothermal Deposits (3B)

Concentrations of uranium in veins within granites occur in the Blue Ridge, Western Piedmont, and eastern Goochland Raleigh terrains (Figure 3.5). They result from the remobilization by hydrothermal fluids of uranium disseminated in large granite bodies. These granites are anomalously enriched in this element (15-30 ppm uranium) compared with average granites (about 4 ppm uranium) and easily leachable (i.e., not hosted by insoluble mineral phases). These occur in Virginia in three different geological situations and ages—Middle to Late Proterozoic granites, Late Paleozoic granitic rocks and pegmatites, and Late Jurassic–Early Cretaceous peralkaline intrusive rocks (Lassetter, 2010).

Middle to Late Proterozoic Granites

Middle to Late Proterozoic granites (Crozet, Old Rag, Marshall granites, Robertson River peralkaline complex, Elk Park Plutonic Group) of the Blue Ridge belt (Figures 3.5, 3.6) contain background uranium concentrations up to 25 ppm (Lassetter, 2010), with an average of 5 to 10 ppm uranium. The average Th/U ratio for the granites is about 10:1, suggesting uranium depletion (Baillieul and Daddazio, 1982).

A study of the uranium resource potential of the Blue Ridge and Piedmont areas was undertaken by Bendix Field Engineering Corporation as part of the Department of Energy's NURE project in the early 1980s. This project led to the discovery of U-Th–enriched cataclastic zones of the Precambrian Lovingston Formation (Figure 3.7) near Charlottesville in the Blue Ridge Belt (Baillieul and

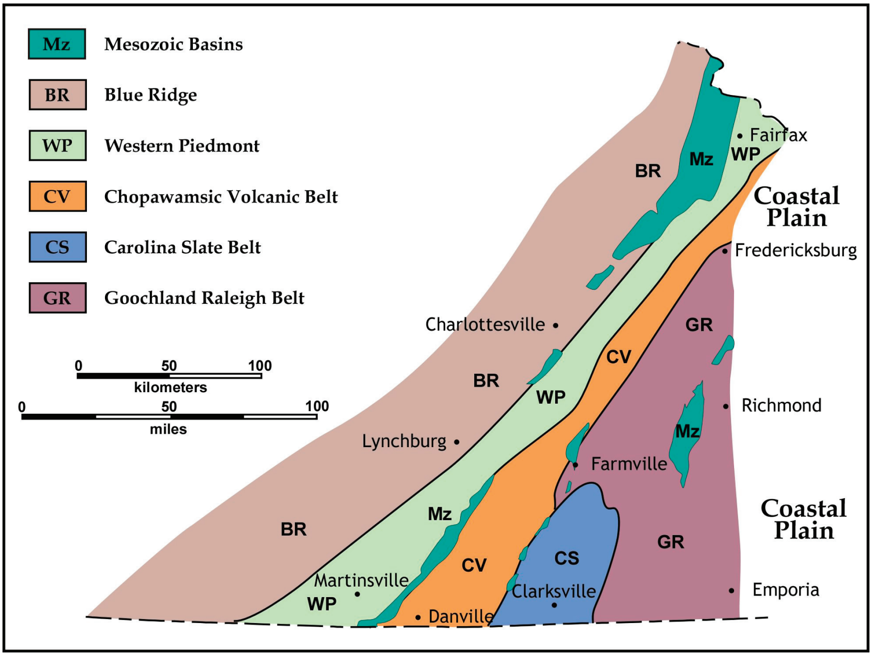

FIGURE 3.5 Generalized structural map showing terrains of the Virginia Piedmont and Blue Ridge areas. SOURCE: Modified from Bailey (1999b).

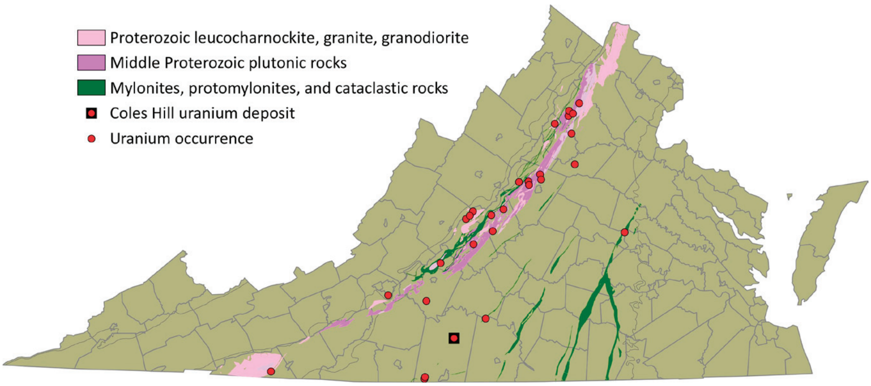

FIGURE 3.6 Distribution of Middle to Late Proterozoic granites and gneisses of the Blue Ridge belt, together with complexly deformed mylonites, shear zones, and cataclasites. SOURCE: Modified from Lassetter (2010).

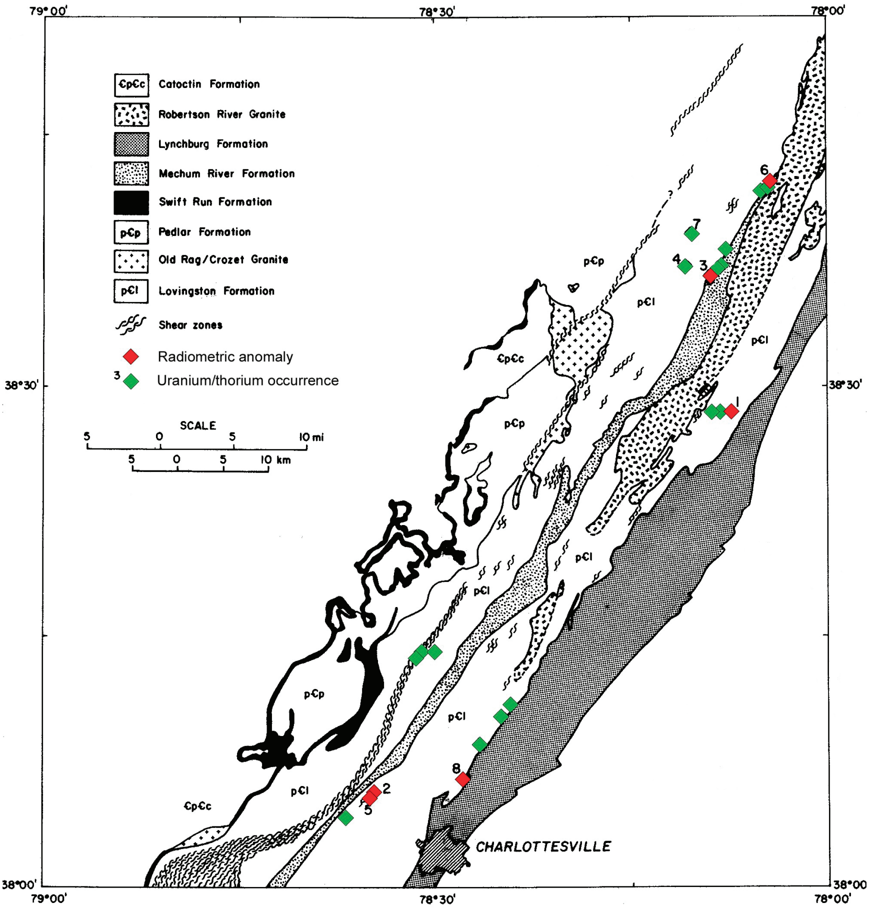

FIGURE 3.7 Uranium/thorium occurrences (green triangles) and radiometric anomalies (red triangles) in the Lovingston Formation, north of Charlottesville. SOURCE: Baillieul and Daddazio (1982).

Daddazio, 1982). The principal radioactive minerals are uranothorite, monazite, and thorogummite occurring with pyrite in the most radioactive rocks. Mineralization has been attributed to magmatic fluids enriched in uranium and thorium during late-stage magmatic differentiation in uranium-rich granitic plutons (Old Rag/Crozet granites) emplaced to the east. With existing economic conditions, this type of mineralization may be of interest for thorium resources but not for uranium.

Late Paleozoic Granites and Pegmatites

Late Paleozoic fractionated granitic rocks include the Petersburg, Leatherwood, Falls Run, Red Oak, and Portsmouth granites (containing up to 16.9 ppm of uranium), and pegmatites with allanite, monazite, autunite, fergusonite, uranophane, and microlite. These deposits occur mostly in the Western Piedmont Belt and eastern Goochland (Figure 3.8).

Anomalous radioactivity from thorium and uranium was detected in a 1974 aeroradiometric survey in an area of crystalline rocks in the Piedmont, just southwest of Powhatan (immediately to the west of Richmond), in the Goochland area of Virginia (Krason et al., 1988). Detailed geological, geochemical (samples of soil, stream sediment, and rock outcrops analyzed for uranium, thorium, cobalt, vanadium, and molybdenum), and ground radiometric surveys of a 3.8-square-mile area were carried out between 1976 and 1978. Total-count ground radioactivity readings defined a distinct northeastward-trending linear anomaly on the axis of the Goochland anticline. In 1986, two core holes were drilled to depths of 140 and 160 ft. The surveys and analyses indicate the radioactivity is mainly caused by thorium present in monazite within the Maidens gneiss (Krason et al., 1988). These two occurrences of radioactive mineralization are dominated by thorium and therefore are not of economic interest in the present market conditions.

Late Jurassic–Early Cretaceous Peralkaline Intrusive Rocks

Late Jurassic–Early Cretaceous nepheline syenite dikes occurring in Augusta County (Figure 3.9) contain up to 22 ppm of uranium. Deposits expected in this geological environment would be Type 1 (fractional crystallization) or Type 3B

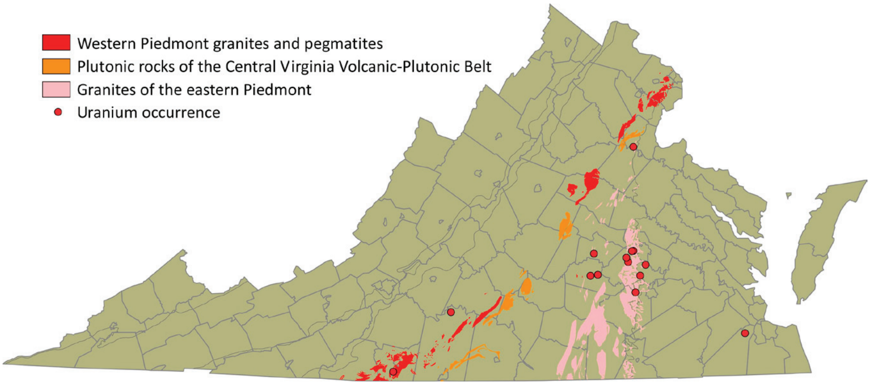

FIGURE 3.8 Distribution of Late Paleozoic fractionated granitic rocks and pegmatites. SOURCE: Modified from Lassetter (2010).

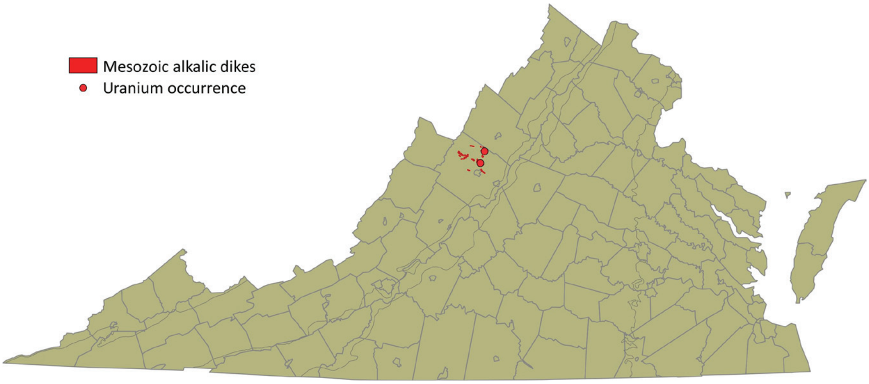

FIGURE 3.9 Location of Late Jurassic–Early Cretaceous peralkaline intrusives in Augusta County. SOURCE: Modified from Lassetter (2010).

(hydrothermal-granitic). Although many of these granitoid massifs initially appear to be favorable targets for uranium exploration of vein-type mineralization, the extensive exploration and coring conducted in these areas during the late 1970s and early 1980s show that the uranium deposits are small, and the discovery of economic uranium deposits would require a considerable effort in new exploration.

Comparable uranium deposits. The most analogous area for the type of deposit (Type 3B) that may exist in such granitoid intrusive rocks occurs in the Variscan belt in France and the southeastern part of Germany, from which about 350,000 tU were extracted from the 1950s to the 1990s, and in the Czech Republic where the Rožná uranium deposit is still mined. These two countries have climatic conditions very comparable to those of Virginia, with a temperate and relatively humid climate, a strong vegetation cover, extensive farming, and relatively high population density.

Synsedimentary Deposits

These types of deposits include Devonian-Mississippian sedimentary deposits in the Appalachian Plateau area of western Virginia and marine phosphorites occurring in the Coastal Plain.

Devonian-Mississippian Sediments

The Devonian-Mississippian black shales (synsedimentary redox trapping; Type 7B) in the Appalachian Plateau area (Figure 3.10) contain approximately

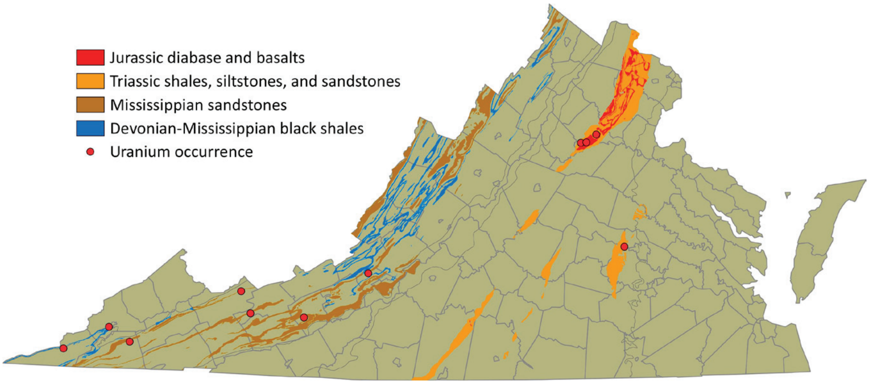

FIGURE 3.10 **Distribution of Devonian-Mississippian sedimentary deposits in the Appalachian Plateau area of western Virginia and Triassic sedimentary rocks and Jurassic basalts of the Piedmont.** SOURCE: Modified from Lassetter (2010).

70 ppm uranium, and Mississippian sandstones contain up to 140 ppm uranium. Because these sediments have much lower uranium grades than the large resources hosted by the alum shales in Sweden (see below), the development of such a resource in Virginia is unlikely to occur in the foreseeable future.

Comparable uranium deposits. The Cambrian-Ordovician alum shales in southern Sweden represent uranium resources of over 1 million tU, and the Ranstad deposit alone— extending over 490 km^2—contains ~254,000 tU at 170 to 250 ppm. Test mining had occurred by the end of the 1970s, but ceased because of the high costs of uranium extraction. These resources are not economic in the present market conditions. Climatic conditions for this part of Sweden are comparable to those of Virginia, except with lower average temperatures.

Marine Phosphorites

Tertiary phosphatic sediments *(synsedimentary crystal-chemical/redox trapping deposits, type 7C*) cover large parts of the Coastal Plain (Figure 3.11), where they locally contain up to 1,350 ppm uranium.

Comparable uranium deposits. Phosphorites in Florida were mined until 1992, with a production of about 900 tons of uranium per year and average grades close to 100 ppm uranium. Phosphorites in Morocco represent by far the largest resource of this type in the world, with several million tons of uranium

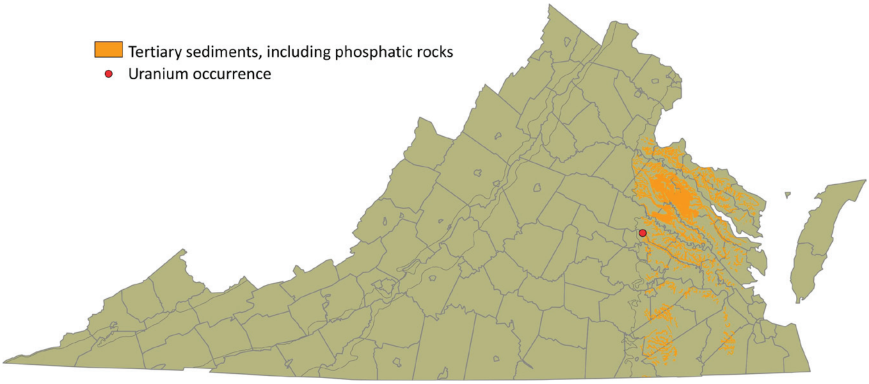

FIGURE 3.11 Distribution of Tertiary sedimentary rocks on the Virginia coastal plain, mostly of Miocene age, that may contain uranium-enriched phosphates. A single sample location with an anomalously high uranium value is shown. SOURCE: Modified from Lassetter (2010).

at an average grade of 100 to 150 ppm uranium (IAEA, 2009). Studies are being undertaken to determine the feasibility of recovering uranium from the Moroccan phosphorites. If uranium production from phosphorites becomes economically attractive, production would start first in Morocco because of the high uranium grades, and the next most economically attractive would be the Florida deposits. Production of uranium from Virginia phosphorites is not expected in the foreseeable future.

Pennsylvanian Coal Ash Deposits (Unconventional Deposit)

Pennsylvanian coal deposits are abundant in the Appalachian Plateau area, where they are extensively mined in open pits and underground. Uranium production from coal ash could occur in the vicinity of the power plants using the coal, but uranium production would not be in the vicinity of the coal mines.

Comparable uranium deposits. Uranium extraction from coal ash is presently being studied in China, to test the extraction of uranium from ash produced by the burning of lignite coal (Morales et al., 1985). This coal has high ash content (20-30 percent) and an average uranium content of 65 ppm (range of 20-315 ppm). With an average uranium content of 125 ppm, annual coal ash produced from three power stations contains about 150 tU. Assuming a uranium recovery rate of 70 percent, 105 tU per year could be produced from this Chinese ash. About 1,100 tU was recovered from lignite ash between 1964 and 1967 in North Dakota.

Synsedimentary Placers (Unconventional Deposit)

Uranium can be a byproduct of thorium–rare earth elements (REE) production from monazite. Monazite itself is recovered as a byproduct of processing heavy mineral sands, mainly for the extraction of ilmenite, rutile, leucoxene, and zircon for the production of titanium and zirconium. Thorium, which averages 6-7 weight percent in monazite, is a byproduct of refining monazite for its REE content. Uranium concentrations in monazite reach several thousand parts per million on average, and thus may represent an additional byproduct of REE and thorium extraction from monazite.

Uranium extraction as a byproduct of REE and thorium recovery from monazite can be expected in the future. However, the extraction of these elements will not be the leading factor for increasing the mining of heavy mineral sands; these driving factors are first titanium and zirconium extraction, and then the REEs, and in last position, thorium. Uranium will be a byproduct with little or no influence on the global extraction of heavy mineral sands.

In 2003, Virginia ranked second in the United States for the production of titanium and zirconium from heavy mineral sands. That year, Iluka Resources produced 360,000 tons of heavy mineral concentrate from Old Hickory placers in Dinwiddie County (Figure 3.12). These placers, up to 50 ft thick, correspond to Pliocene nearshore beach and dune sands deposited 3 million to 4 million years ago when the shoreline of the Atlantic Ocean was near Richmond. The heavy mineral concentration averages 8 weight percent, with about 80 percent of the heavy minerals being ilmenite, leucoxene, rutile, and zircon, and the remaining part containing monazite, REE, Th, U, and phosphate. Note that between 1880 and 1918, almost all domestic production of monazite, for thorium production,

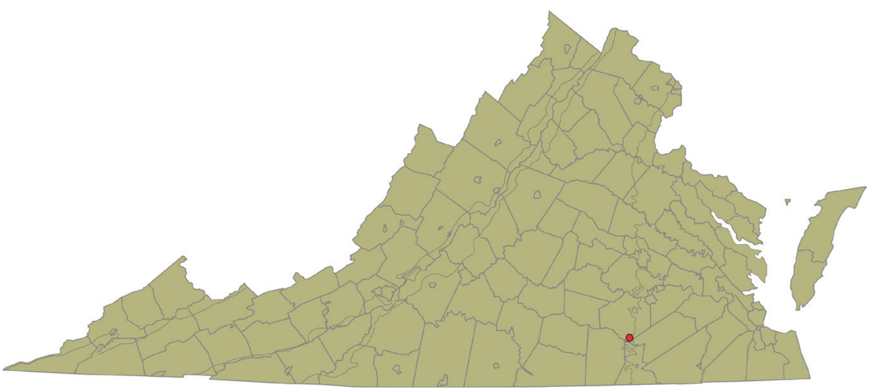

FIGURE 3.12 Location of the Old Hickory placers in Dinwiddie County. SOURCE: VA DMME Division of Geology and Mineral Resources (http://www.dmme.virginia.gov/DMR3/heavyminsand.shtml; accessed October 2011).

came from the heavy minerals sands of the Piedmont area of North Carolina and South Carolina, with resources of 857,000 tonnes of monazite at 5.61 weight percent ThO_2 and 0.36 weight percent U_3O_8 (Overstreet, 1967).

Comparable uranium deposits. Australia and India have considerable uranium resources in placer deposits, but they are not economic to mine in the present market conditions. However, a supply shortage of the REEs as a consequence of recent policy decisions by China may lead to a renewal of REE extraction from monazite. In addition, some countries—India and Russia in association with the United States—are developing thorium reactors that should increase thorium demand and thus may increase the interest of monazite processing for simultaneous REE, thorium, and uranium recovery.

Diagenetic Hydrothermal Deposits (Type 4)

These deposits are sandstone-hosted, and may occur in Pennsylvanian to Mississippian and Triassic age lithological units in Virginia. Some of the fine- to coarse-grained Pennsylvanian to Mississippian continental sandstones (Figure 3.8) contain paleochannels that acted as permeable aquifers for the circulation of uranium-bearing diagenetic fluids, and with reductants that caused uranium precipitation. These sandstones—for example, the Harlan sandstone, intercalated with discontinuous coal beds; the Wise Formation, containing coal beds and volcanic ash that may have been a uranium source; the Gladeville sandstone, with coal beds and plants; and the Lee, Pocahontas, New River, and Hinton Formations—can contain up to 140 ppm uranium.

The Upper Triassic sandstones of the Newark Supergroup contain layers of fine- to coarse-grained continental sandstones with paleochannels, intercalated with carbonaceous shales and coal and bituminous occurrences. These constitute the required elements for the formation of roll-front-type uranium deposits. Moreover, high methane concentrations have been reported in the Richmond and Taylorsville basins, and uranium anomalies associated with phosphate-rich layers represent additional favorable criteria for the occurrence of uranium deposits.[1] The airborne radiometric map of the Culpeper and Barboursville Basins (Leavy et al., 1982) shows an area of elevated uranium levels extending through Somerset and Barboursville, between Hardwick and Cowherd mountains. Uranium levels up to six times the regional average that were found in this area attracted exploration activity, and before the moratorium on uranium mining was enacted, some 2,000 acres in Orange County was under lease to uranium exploration companies. Some of these anomalies are the result of radioactive components brought in by fertilizer, but most of the high anomalies south of Herndon are in red-brown siltstone (Leavy et al., 1982). Austin and D'Andrea (1978) suggest that the fluvial

[1]Presentation by J. Beard, Virginia Museum of Natural History, to the committee in Richmond, February 7, 2011.

rocks of the Triassic-Jurassic Culpeper/Barboursville Basin lack the requisite permeability to have acted as hosts for uranium deposits. Most of the sandstones and conglomerates contain a large amount of silt- and clay-sized material, which results in extremely low permeability.

There appears little likelihood that economic uranium deposits associated with these sandstones will be discovered in the foreseeable future. The Pennsylvanian and Mississippian sandstones have been extensively drilled and mined for coal without the discovery of significant uranium mineralization, and the Triassic basin in Virginia does not appear to contain suitable lithologies. Consequently, the use of ISL/ISR technology to mine sandstone-hosted uranium deposits in Virginia is unlikely in the foreseeable future.

Comparable uranium deposits. Roll-front-type deposits in Wyoming (Finch, 1996) represent equivalents of deposits that may occur in Pennsylvanian, Mississippian, or Triassic sandstones. Carboniferous sandstones in the Arlit area of Niger, belonging to the tectonolithologic category of uranium deposits, may also have some similarities to the continental sandstones in Virginia. They contain more than 150,000 tU at grades of 0.2 to 0.5 percent. The climatic conditions in this area are extremely arid, with high average temperature and extremely low rainfall.

Hydrothermal Metasomatic Deposits Associated with Alkali Metasomatism (Type 6A)

The Coles Hill deposit, located in the Pittsylvania County, occurs within a fault-bounded wedge of the sheared and highly potassic calcalkaline Leatherwood Granite (Figures 3.13, 3.14), along the Chatham Fault Zone at the northwest margin of the Triassic age Danville Basin (Jerden, 2001). The Leatherwood Granite, a component of the Martinsville Igneous Complex, was emplaced during the Late Ordovician (~442 Ma) in the Chopawamsic Volcanic Belt (Figure 3.5). Amphibolite layers are common within the granite. The deposit is partly covered by Danville Basin sedimentary rocks (Figure 3.13). The mineralized orebodies are characterized by intense sodium metasomatic alteration associated with quartz dissolution. The ore deposit is mainly contained within two approximately 350-m-long and 250-m-wide cylindrical bodies, within which the orebodies form lenticular layers below the Chatham Fault Zone (Figure 3.14).

The enclosing rocks are dominantly granitoids, with ~30 percent quartz by volume. The mineralized rocks and their alteration envelope are poor in quartz because the hydrothermal processes associated with the genesis of the deposit lead to nearly complete quartz leaching and albitization of these rocks.

Uraninite and coffinite are the main ore minerals—these are easy to leach, but they are hosted by a hard rock (Figure 3.15) that is difficult to crush. The Coles Hill ore contains high concentrations of phosphorus, with most ore grade samples ranging from 1 to 9 weight percent P_2O_5, but the concentrations of other trace elements are similar to those of the enclosing granitic gneisses (Jerden,

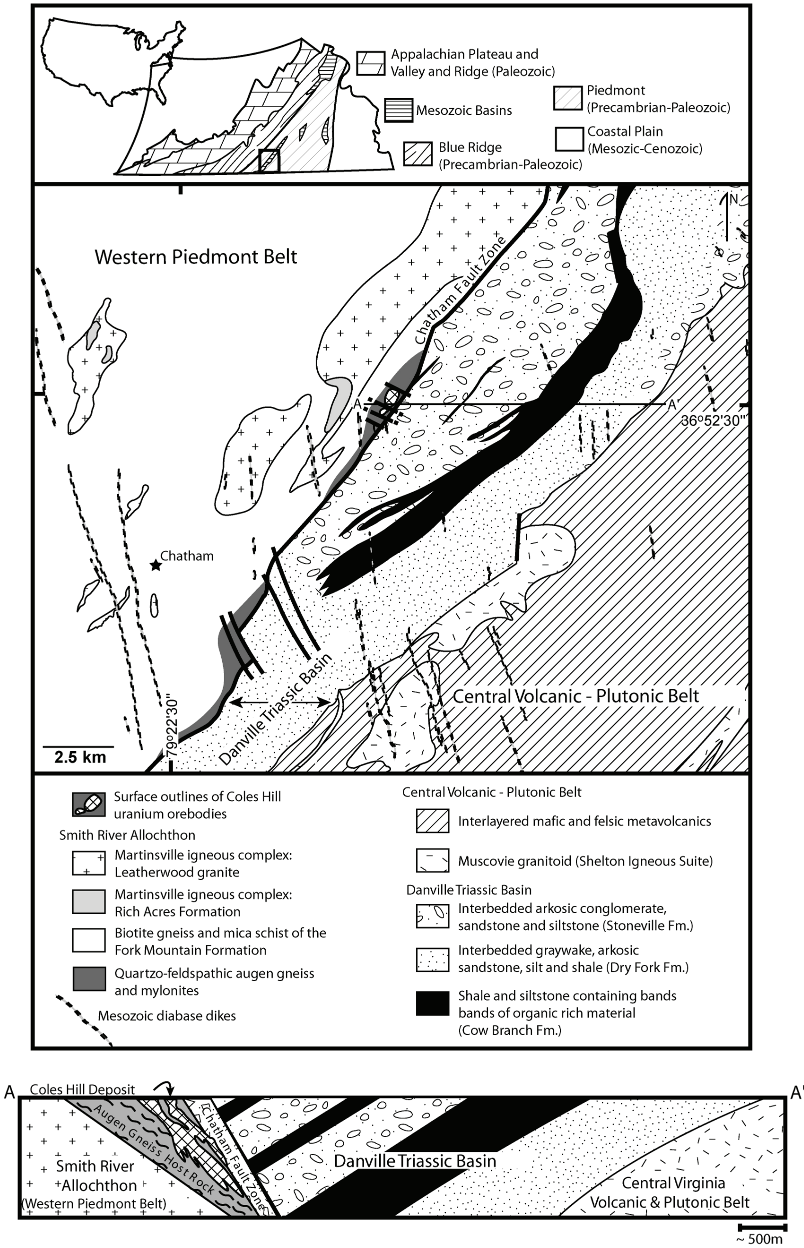

FIGURE 3.13 Geological map and cross section of the Coles Hill region in Pittsylvania County showing the location of the Coles Hill deposit hosted by deformed granitic rocks (augen gneisses and mylonites) of the Leatherwood Granite, west of the Chatham Fault Zone and underlying the Danville Triassic Basin. SOURCE: Jerden (2001).

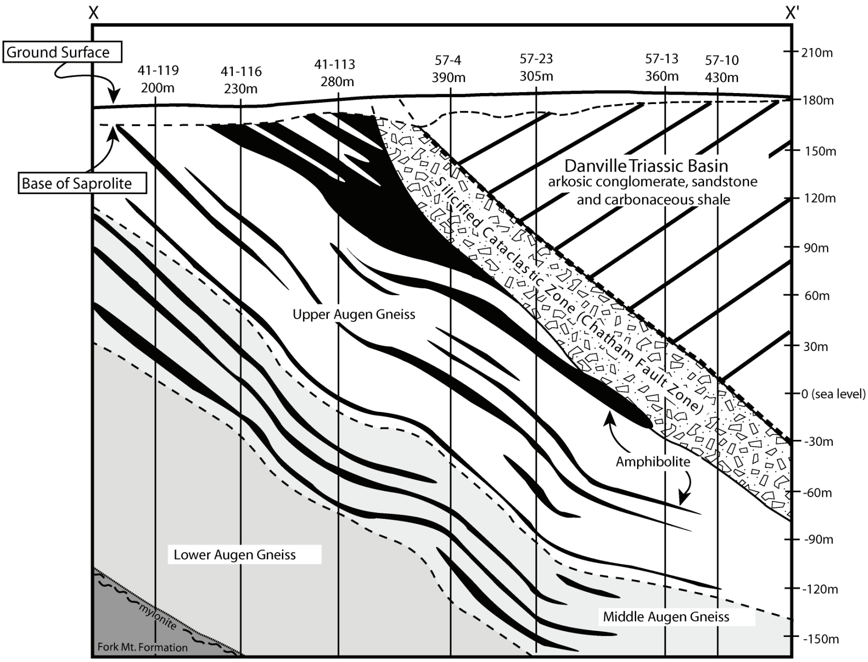

FIGURE 3.14 Detailed geological cross section of the Coles Hill area constructed from Marline Uranium Corporation drill hole data (Marline Uranium Corporation, 1983). Vertical holes drilled within the plane of the cross section are shown as solid lines and are identified by well number and total well depth. SOURCE: Jerden (2001).

2001). Because of the abundance of feldspars and carbonates, extraction of uranium by an alkali leach process may be needed, but acid leaching would also need to be considered.

The Coles Hill deposit contains significant uranium resources at grades comparable to average grades for uranium deposits worldwide, and the main uranium-bearing minerals are easily leachable in acidic or alkaline solutions. Resource calculations for this deposit are shown in Table 3.2.

Comparable uranium deposits. The Cachoera deposit at Lagoa Real in Brazil (Cuney and Kyser, 2008) and the Novokonstantinovka deposit of the Central Ukraine district (Cuney et al., 2012) are both being mined at present, with production rates of several hundreds of tonnes of uranium per year and resources of several hundreds of thousands of tonnes of uranium. The Cachoera deposit in Brazil is an open-pit mine at present, and underground workings are being developed. The mine has been developed recently (<10 years) and therefore uses the best practices for uranium mining and ore processing.

FIGURE 3.15 **Drill core from the Leatherwood Granite showing highly sheared and mineralized granite.** The average U_3O_8 percentage in this 10-foot core section is 0.679 percent. SOURCE: Wales (2010).

TABLE 3.2 Uranium Resources of the Cole Hill Deposits

	Measured[a]			Indicated[a]			Total[a]		
Cutoff % U_3O_8	Tons[b]	% U_3O_8[c]	Pounds[d] U_3O_8	Tons[b]	% U_3O_8[c]	Pounds[d] U_3O_8	Tons[b]	% U_3O_8[c]	Pounds[d] U_3O_8
0.100	0.755	0.228	3.45	6.27	0.215	26.9	7.03	0.216	30.4
0.075	1.35	0.164	4.44	24.0	0.116	55.9	25.4	0.119	60.4
0.050	2.28	0.124	5.65	35.4	0.101	71.7	37.7	0.103	77.4
0.025	6.62	0.064	8.42	92.1	0.060	111.0	98.7	0.060	119.0

[a]Total tonnage above cutoff grade and average weight % U_3O_8 of that tonnage.
[b]Millions of short tons based on a rock density of 2.56 g/cc.
[c]Weight %.
[d]Millions of pounds in place.
SOURCE: NI 43-101 compliant resource estimates prepared by Behre Dolbear and Marshall Miller and Associates, Inc., April 2009 (Available at http://www.santoy.ca/s/ColesHill.asp; accessed August 11, 2011).

URANIUM RESOURCES, RESERVES, AND MARKETS

The global uranium market and uranium prices reflect the fluctuating balance between the demand for uranium for nuclear power generation, and the production from mining/processing and from additional sources such as recycling spent fuel and reprocessing highly enriched uranium and plutonium from decom-

missioned nuclear weapons. The global uranium market in the broadest sense consists of uranium resources and reserves, demand for uranium, and uranium production. The United States has the greatest number of nuclear reactors in the world at present, and therefore the greatest demand for nuclear fuel. However, in 2010 the U.S. domestic uranium mining industry only produced 1,660 metric tonnes (tU) of the 18,376 tU needed to operate the 104 nuclear power plants across the nation, amounting to a domestic deficit of approximately 16,716 tU (~90 percent deficit) (WNA, 2011d). Although this deficit is filled at present by uranium imports and by dilution (downblending) of uranium recovered from nuclear warheads (see below). However, with the cessation of the downblending program in 2013, and increased demands for fuel for the more than 60 new nuclear reactors under construction worldwide, additional demand will be placed on the uranium market (WNA, 2011d).

Uranium Demand

Demand for uranium is driven by the electric power industry's need for fuel for nuclear power generation facilities; in 2009, 435 commercial nuclear reactors were connected to the worldwide electric grid in the 30 countries with nuclear power generation, and another 63 reactors are under construction (WNA, 2011c). In 2011, these reactors will require 81,134 short tons of U_3O_8 concentrate (yellowcake), equivalent to 68,971 tU, to generate 375 Gigawatts (GWe) of net generation capacity. The Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA) project demand out to 2035, with both low- and high-demand scenarios. The low-demand projection is for 511 GWe, a 37 percent increase compared with 2008 demand. The high-demand scenario projects a nuclear power generation demand for 782 GWe, a 110 percent increase (NEA/IAEA, 2010).

In 2011, the United States will require 18,376 tU of U_3O_8 concentrate (20,256 short tons) to fuel the nation's 104 operating nuclear reactors (WNA, 2011c), accounting for 20 percent of U.S. electricity generation (USEIA, 2011c). As of December 2009, the United States had one reactor under construction, 11 planned, and 19 proposed, equivalent to approximately 40 GWe of new capacity (WNA, 2011a). Projections by the NEA/IAEA show a range from modest (low-demand scenario) to dramatic (high-demand scenario) increased demands by U.S. nuclear power generation facilities for U_3O_8 fuel (NEA/IAEA, 2010) (Figure 3.16).

Uranium Resources

In the United States, reserves of uranium are defined by the U.S. Department of Energy's Energy Information Administration (USEIA) as "estimated quantities of uranium in known mineral deposits of such size, grade, and configuration

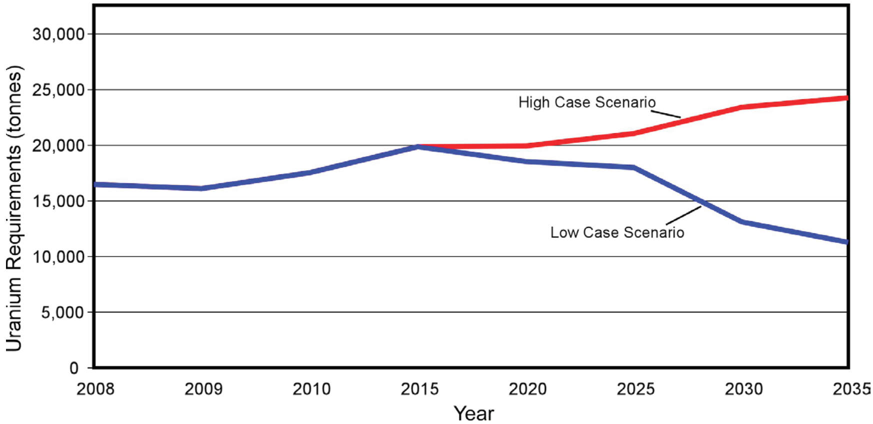

FIGURE 3.16 Projections for U.S. uranium requirements to fuel nuclear reactors through 2035. SOURCE: Compiled from data in NEA/IAEA (2010).

that the uranium could be recovered at or below a specified production cost with currently proven mining and processing technology and under current law and regulations."[2] The U.S. Securities and Exchange Commission (SEC) regulates public disclosure of exploration results and the definition of mineral resource and reserve estimates (Box 3.2).[3] The SEC defines a reserve as a "mineral deposit which could be economically and legally extracted or produced at the time of the reserve determination." Internationally, the IAEA and Nuclear Energy Agency (NEA) define resources based on differing levels of certainty—Identified Resources, which include Reasonably Assured Resources (RAR) and Inferred Resources (EAR), as well as Undiscovered Resources which include Prognosticated Resources (PR) and Speculative Resources (SR).

The NEA/IAEA compilation (NEA/IAEA, 2010) for worldwide uranium resources in a range of resource categories for different cost ranges is presented in Table 3.3, and the RARs in the United States are shown in Table 3.4.

For RAR, WNA estimated that the nuclear energy's fuel supply infrastructure should be able to meet world demand in the short term, but expansion will be needed across the entire fuel cycle beyond 2020 (Figure 3.18) (WNA, 2009).

When considered on a country-by-country basis, three countries—Australia, Kazakhstan, and Canada—contain 52 percent of the world's Identified Resources of uranium at the < $130/kg cost point (NEA/IAEA, 2010), corresponding to 2,810,100 tonnes (3,097,605 short tons). However, a substantial component of these resources are contained in the giant Olympic Dam deposit in Australia

[2]EIA Glossary; see http://www.eia.gov/tools/glossary/index.cfm; accessed September 2011.
[3]http://www.sec.gov/about/forms/industryguides.pdf; accessed December 2011.

BOX 3.2
International Guidelines for Defining Mineral Resources

The U.S. guidelines for defining mineral materials, such as uranium, differ from other international guidelines and standards. The U.S. Securities and Exchange Commission (SEC) regulates the disclosure of exploration results and the definition of mineralized materials and reserves under its Industry Guide 7 criteria.[a] The Canadian Securities Administrators have a different mineral resource classification system—the National Instrument 43-101 (NI 43-101).[b] Australasia adheres to the JORC (Joint Ore Reserves Committee) Code, and compliance is mandatory for companies listed on the Australian Stock Exchange. The Canadian NI 43-101 and JORC Code are similar, as they generally follow international guidelines set by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO),[c] whereas the SEC guidelines differ from the NI 43-101 and JORC guidelines in some key areas.

In the late 1990s, CRIRSCO developed an *International Framework Classification for Mineral Reserves and Mineral Resources*. This committee included representatives from Australasia, Canada, Chile, Europe, and the United States. CRIRSCO defined mineral resources and reserves and their respective subcategories, Measured, Indicated, and Inferred Resources, and Proved and Probable Reserves (Figure 3.17). Following the CRIRSCO Agreement, the U.S. Society for Mining, Metallurgy, and Exploration (SME) released guidelines in 1999 (as did equivalent Canadian and Australasian organizations). However, The United States was the one CRIRSCO country whose regulator—the SEC—did not recognize the SME reporting standard and thus the CRIRSCO agreement guidelines.

Instead, the SEC published its own guidelines, delineated in its Industry Guide 7, “Description of Property by Issuers Engaged or to Be Engaged in Significant Mining Operations.” The main differences between the SEC and CRIRSCO guidelines are that the SEC has (1) a requirement of a standardized price based on the prevailing 3 years; (2) a restriction on the disclosure of proved and probable mineral reserves while other mineralized material is permitted (note that “mineralized material” is not clearly defined in the SEC guidelines); (3) a definition of a reserve as a “part of a mineral deposit which could be economically and legally extracted or produced at the time of the reserve determination”[d]; and (4) no clear

where the primary production is copper from a hydrothermal orebody, with subsidiary production of uranium, gold, and silver. The dominating effect of the Olympic Dam and other Australian uranium resources are also reflected in RAR comparisons (Figure 3.19).

Annual, worldwide requirements for fuel for existing power reactors amounts to about 67,000 tU. The world’s presently known Identified Resources of uranium, exploitable at or below $80 per kilogram of uranium, are some 3.75 million tonnes (Table 3.3) (NEA/IAEA, 2010). Existing known identified resources, based on present-day reactor technologies and if the resources are developed, are

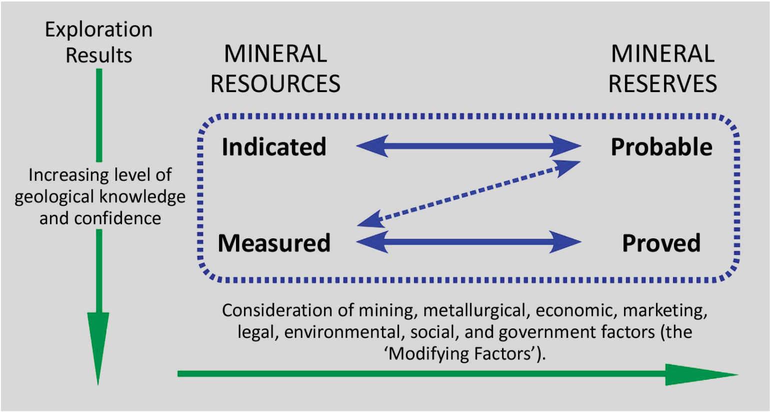

FIGURE 3.17 Mineral resource and reserve flow diagram. Certainty is improved moving down and to the right. SOURCE: Courtesy of Committee for Mineral Reserves International Reporting Standards.

requirement for a competent person to define the resource/reserve. Although there have been discussions between SME and SEC regarding the adoption in the United States of the internationally standardized set of guidelines, at present the Industry Guide 7 remains in effect for public reporting of mineralized materials and reserves.

[a]http://www.sec.gov/about/forms/industryguides.pdf.
[b]http://www.cim.org/committees/NI_43-101_Dec_30.pdf.
[c]http://www.crirsco.com/background.asp.
[d]http://www.sec.gov/about/forms/industryguides.pdf.

sufficient to last for more than 50 years at today's rate of usage—a figure higher than for many widely used metals. However for these resources to be developed, a range of challenges will have to be addressed:

- ***Financial***. For example, Australia has by far the largest RAR of uranium in the world (Figure 3.19), but a large part correspond to the huge Olympic Dam deposit where uranium production is relatively small (about 4,000 tU) because it is tied to the production of copper and gold. The grade of the deposit (about 250 ppm U) does not permit uranium to be mined for its own value. A four- to

TABLE 3.3 Worldwide Uranium Resource Quantities for Different Production Cost Ranges and Different Degrees of Confidence, as of January 2009

Cost		Identified Resources (RAR + Inferred Resources)		Reasonably Assured Resources		Inferred Resources	
		short tons	tonnes	short tons	tonnes	short tons	tonnes
<$18/lb U	<$40/kg U	877,881	796,400	628,207	569,900	249,784	226,600
<$36/lb U	<$80/kg U	4,124,739	3,741,900	2,773,525	2,516,100	1,351,213	1,225,800
<$59/lb U	<$130/kg U	5,956,890	5,404,000	3,885,537	3,524,900	2,071,353	1,879,100
<$118/lb U	<$260/kg U	6,951,506	6,306,300	4,414,206	4,004,500	2,537,300	2,301,800

SOURCE: NEA/IAEA (2010).

TABLE 3.4 U.S. Uranium Resources in the Reasonably Assured Resources Category for Different Cost Ranges, as of January 2009

Cost		Reasonably Assured Resources	
$/lb U	$/kg U	short tons	tonnes
<18	<40	0	0
<36	<80	42,990	39,000
<59	<130	228,619	207,400
<118	<260	520,401	472,100

SOURCE: NEA/IAEA (2010).

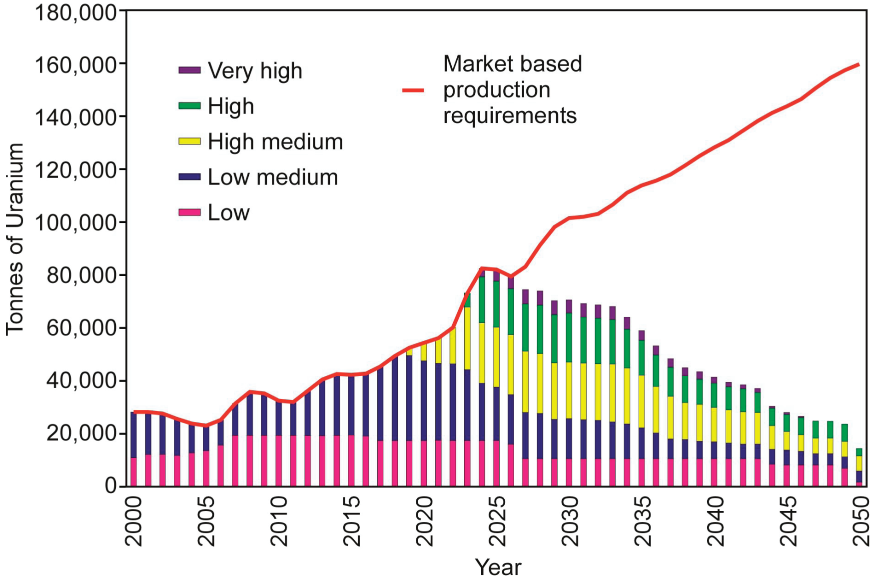

FIGURE 3.18 Increased cost of uranium production over time that will be required to meet projected increases in demand. SOURCE: Modified from IAEA (2001).

fivefold increase in uranium production from the Olympic Dam deposit will require an investment of about 15 billion Australian dollars.

- ***Technical***. Development of improved or new ore processing methodologies will be required for production of uranium from complex ores (e.g., extraction of uranium from phosphates, from refractory minerals in deposits associated with peralkaline rocks).
- ***Political***. Some countries or provinces have established bans on uranium exploration and mining.

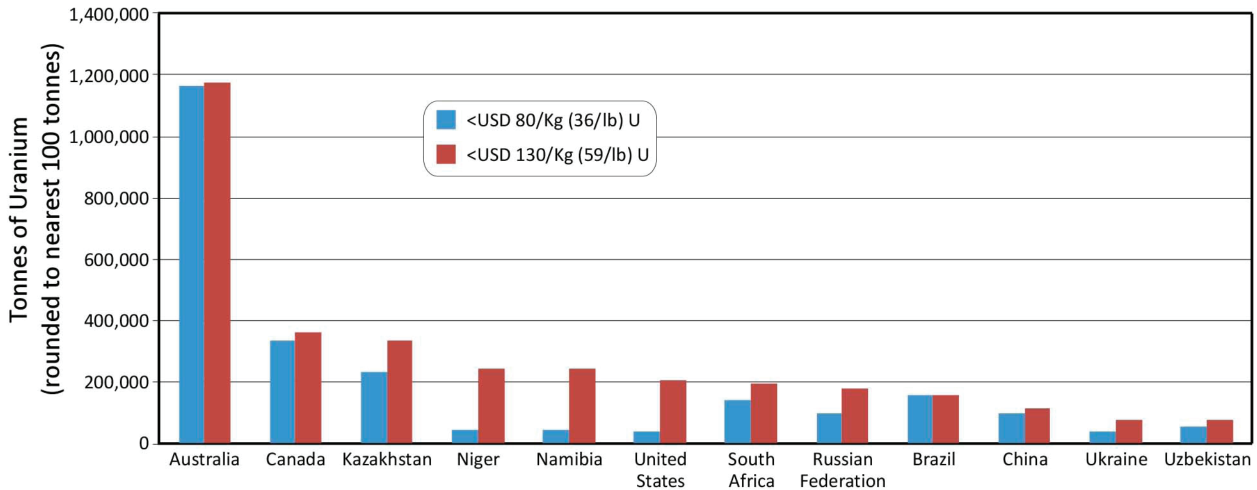

FIGURE 3.19 Reasonably Assured Resources of uranium in 2009 at the < \$80/kg (< \$36/lb) and < \$130/kg (< \$130/lb) cost points for the 12 major uranium mining countries (in tonnes). SOURCE: Compiled from NEA/IAEA (2010).

- ***Security***. Development of uranium mines in Niger is currently hampered by security issues in the northern part of the country.
- ***Development duration***. The time for development of a mine from the beginning of exploration until initial production has been steadily increasing (now averaging about 15 years). This problem is particularly sensitive at present because of several issues: After nearly 20 years of extremely low exploration rates all over the world and with widespread exploration only restarting since 2004, a new generation of geologists specializing in uranium exploration, as well as mining and metallurgical engineers specializing in uranium processing, will need to be educated; and tighter regulations for uranium mining have considerably increased the duration for the licensing of the new uranium mines.
- ***Economics***. Because of the present economic crisis, uranium spot prices are decreasing and fluctuating while the price of uranium production is continuously increasing.

Uranium Production

Uranium supply is partly from production of new ore from mining, and partly from secondary sources of already mined uranium. World uranium production in 2009 fulfilled 74 percent of world reactor requirements (57,061 short tons of U_3O_8 or 43,880 tU) out of the total requirement for 59,065 tU (76,808 short tons) of U_3O_8. The remaining 26 percent came from secondary sources such as existing stockpiles held by government and commercial entities, low enriched uranium from downblending of highly enriched uranium recovered from nuclear warheads ("Megatons to Megawatts"), and reenrichment of depleted uranium tails and spent fuel reprocessing (NEA/IAEA, 2010). Highly enriched uranium is about 97 percent ^{235}U and has to be diluted about 25:1 with depleted uranium (or 30:1 with enriched depleted uranium) to reduce it to about 4 percent ^{235}U for use in power reactors. From 1999 to 2013, when the program is projected to end, the dilution of 30 tonnes of highly enriched uranium is displacing about 9,000 tU mine production per year (NEA/IAEA, 2010).

In the United States and Canada, the nuclear fuel cycle is an "open" or "once-through" system where spent nuclear fuel is not reprocessed. In France, Japan, and a few other countries, a "closed" fuel cycle is used. In a closed fuel cycle, the spent nuclear fuel is sent to reprocessing operations for the separation of waste products so that the plutonium and uranium can be used as recycled fuel in reactors (Dyck and Crijns, 2011). Reprocessed uranium from spent nuclear fuel accounts for approximately 2,000 to 2,500 tonnes (or 3.3 to 4.2 percent) displacement of natural uranium from mines (IAEA, 2007). There are no U.S. reprocessing plants currently in operation, and the one facility in Savannah River, South Carolina, is years away from completed licensing by the U.S. Nuclear Regulatory Commission (USNRC, 2011). The main spent fuel reprocessing plants operate in France and (until August 2011) in the United Kingdom, with capacity of

over 4,000 tonnes of spent fuel per year. Russia, Japan, Belgium, Germany, and Switzerland also recycle plutonium for mixed oxide (MOX) fuel elements, but to a lesser extent. The plutonium for MOX fuel can be obtained from spent fuel rods (as is the case in France) or from weapons-grade surpluses (as is the case in a possible U.S. MOX fuel scenario). About 200 tonnes of MOX are used each year, equivalent to about 1,700 tU from mines.

Although uranium was produced in 20 countries in 2010, eight countries (Kazakhstan 33 percent, Canada 18 percent, Australia 11 percent, Namibia 8 percent, Niger 8 percent, Russia 7 percent, Uzbekistan 4 percent, and the United States 3 percent) account for more than 92 percent of the world's uranium production. Only two countries—Canada and South Africa—produce enough uranium to meet domestic demand; conversely, other countries having no nuclear power generation capacity produce substantial quantities of uranium.

Overall, world uranium primary production increased steadily for the decade to 2009 (Figure 3.20; Table 3.5), with Kazakhstan, Namibia, Australia, Russia, and Brazil showing marked increases between 2006 and 2009 to offset decreased production in Canada, Niger, the United States, and the Czech Republic (NEA/IAEA, 2010). In North America, production is dominated by Canada, which produced 8,500 tU in 2008.

In the United States, uranium was produced at six locations in the third quarter of 2011. White Mesa Mill, near Blanding, Utah, is the only conventional uranium processing facility currently operating in the United States, processing

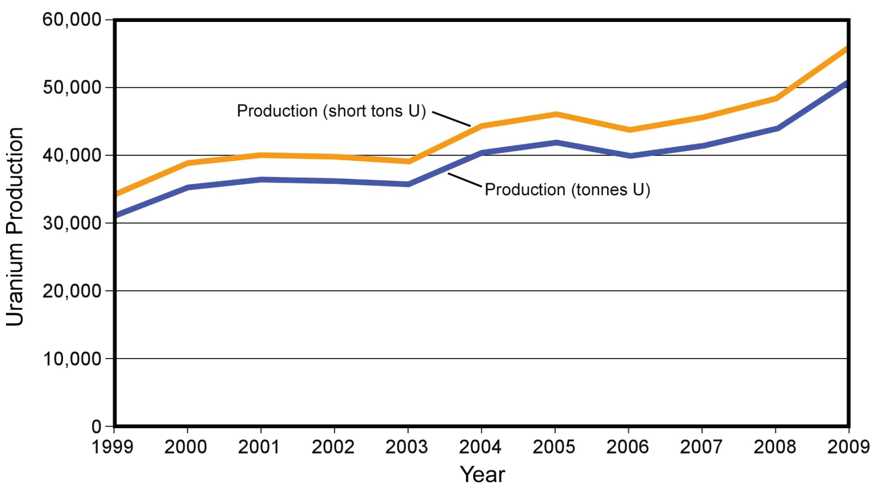

FIGURE 3.20 Production of uranium worldwide in metric tonnes and short tons from 1999 to 2009. SOURCE: WNA (2011b).

TABLE 3.5 Production of Uranium in Tonnes of U_3O_8 from Mines Between 2003 and 2010

Country	2003	2004	2005	2006	2007	2008	2009	2010
Kazakhstan	3,300	3,719	4,357	5,279	6,637	8,521	14,020	17,803
Canada	10,457	11,597	11,628	9,862	9,476	9,000	10,173	9,783
Australia	7,572	8,982	9,516	7,593	8,611	8,430	7,982	5,900
Namibia	2,036	3,038	3,147	3,067	2,879	4,366	4,626	4,496
Niger	3,143	3,282	3,093	3,434	3,153	3,032	3,243	4,198
Russia	3,150	3,200	3,431	3,262	3,413	3,521	3,564	3,562
Uzbekistan	1,598	2,016	2,300	2,260	2,320	2,338	2,429	2,400
USA	779	878	1,039	1,672	1,654	1,430	1,453	1,660
Ukraine (est)	800	800	800	800	846	800	840	850
China (est)	750	750	750	750	712	769	750	827
Malawi	—	—	—	—	—	—	104	670
South Africa	758	755	674	534	539	655	563	583
India (est)	230	230	230	177	270	271	290	400
Czech Repub.	452	412	408	359	306	263	258	254
Brazil	310	300	110	190	299	330	345	148
Romania (est)	90	90	90	90	77	77	75	77
Pakistan (est)	45	45	45	45	45	45	50	45
France	0	7	7	5	4	5	8	7
Germany	104	77	94	65	41	0	0	0
Total world	**35,574**	**40,178**	**41,719**	**39,444**	**41,282**	**43,853**	**50,772**	**53,663**
Tonnes U_3O_8	41,944	47,382	49,199	46,516	48,683	51,716	59,875	63,285
Percentage of world demand			65	63	64	68	78	78

NOTE; 1 tonne of uranium = 1.1792 tonnes of U_3O_8. Estimated production for those countries that do not provide precise numbers to the IAEA are indicated by "est."
SOURCE: WNA (2011d).

ore from mines in Colorado, Utah, and Arizona.[4] There are currently six ISL/ISR operations in the United States—the Alta Mesa Project and the Hobson ISR Plant/La Palangana operation in Texas; the Crow Butte operation in Nebraska; and the Smith Ranch-Highland Operation and the Willow Creek Project in Wyoming (USEIA, 2011b).[5] U.S. production increased markedly from 2003 to 2006 (Figure 3.21), but then slowed because of operational challenges and lower uranium prices with total production in 2008 of 1,492 tU (1,910 short tons); by 2010 production had risen to 1,921 tU (2,119 short tons) (USEIA, 2011a; NEA/IAEA, 2010).

Uranium Prices

All mineral commodity markets tend to be cyclical, with sharp price rises and falls as a result of demand variability and perceptions of scarcity. The history of uranium price fluctuations has to be considered in two different periods. Before the 1970s, uranium prices were not controlled by the open market like other resources because the predominant use was by the military for nuclear weapons. As a result, uranium deposits were mined during this time without the economic costs of production being the top priority and with little consideration of the risks associated with uranium mining.

From the early 1980s, uranium prices have essentially followed the fluctuations of oil prices (Figure 3.22). The 1970s' oil crises led to a sharp increase of uranium prices in the mid-1970s. Then, as oil prices declined in the early eighties, there were depressed uranium prices for the 1980s and 1990s with spot prices well below the cost of production for most uranium mines. The Chernobyl nuclear accident in 1986 occurred during a period of continuous uranium price decline, and does not seem to have had a significant impact on uranium prices. During this time, the uranium market was dominated by the liquidation of inventories—both commercial and military—and by the low oil prices. As a result, the uranium price was depressed and production and exploration efforts were cut back.

Spot uranium prices started to recover strongly late in 2003, coinciding with increased oil prices and dramatic increases in the demand for nuclear energy emerging from China, India, and Russia. Uranium prices reached a maximum during the summer of 2007, in part because of speculation. The economic crisis beginning in September 2007 again led to a decline of oil and uranium prices, but then oil and uranium prices slowly increased again until the Fukushima accident in Japan. Since the Fukushima accident, uranium prices have slowly declined from a maximum of $73 down to $49 per pound at the beginning of September 2011, although they had risen to $54 per pound 2 weeks later. The share prices of

[4] Additional information on the White Mesa uranium mill and Dennison Mine operations is available at http://www.denisonmines.com/Document/Details/121; accessed December 2011.

[5] http://www.eia.gov/uranium/production/quarterly/.

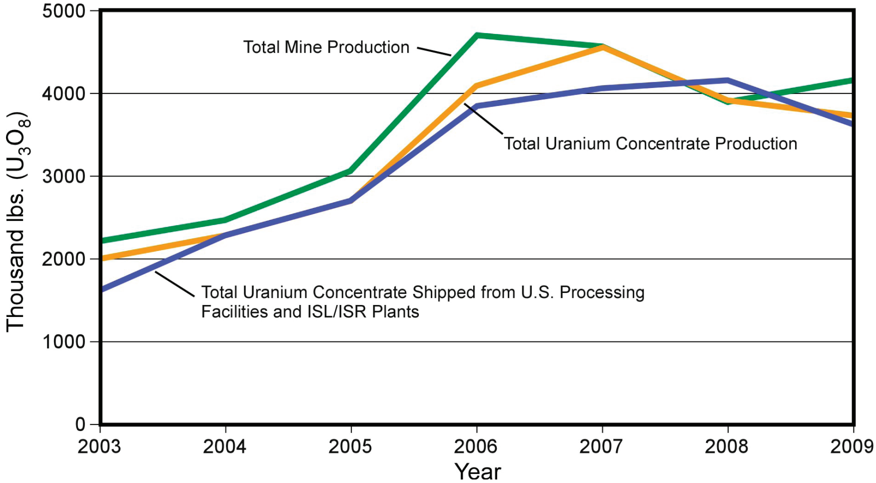

FIGURE 3.21 U.S. uranium production data for 2004-2009, with estimated data for 2003. SOURCE: USEIA (2011a).

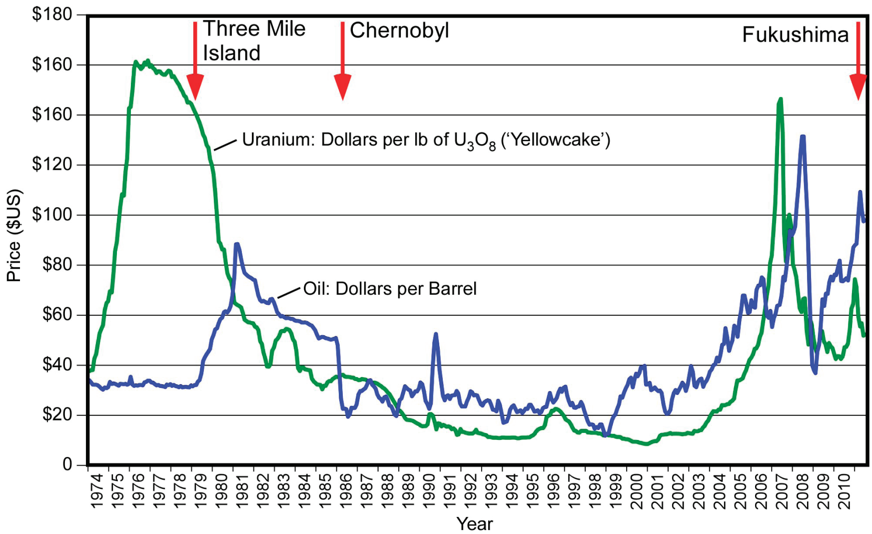

FIGURE 3.22 History of monthly inflation-adjusted spot uranium prices and oil prices from 1974 to 2011, together with the major accidents at nuclear power plants. SOURCES: TradeTech (uranium) and U.S. Energy Information Administration (oil); inflation adjustment from U.S. Department of Labor's Bureau of Labor Statistics.

smaller uranium companies have also been affected negatively by the Fukishima accident—with an average stock decline of 40 percent—because they are dependent on capital markets to raise money to explore for new deposits. The long-term price of uranium has been less affected, with a decline from pre-Fukushima levels of $70-$73 per pound down to $68 per pound. Short-term growth of the nuclear industry has continued—there were 62 reactors under construction worldwide before the Fukushima accident and there are still the same 62 reactors under construction today. In addition, there have been no reports of operating uranium mines shutting down. Germany has announced a decision to phase out its reliance on nuclear power by 2022, but this decision is very recent and there is uncertainty as to whether Germany will be able to maintain it in the future. For example, Sweden announced in 1980 that it would phase out nuclear energy, but changed its decision in 1997; and Germany's decision in 2000 to phase out the use of nuclear energy was initially delayed in 2010.

According to WNA (2011a), it is still too early to assess the full impact of the Fukushima accident on the world nuclear fuel market. Despite the permanent closure of a number of reactors in Japan and Germany and slowdowns in some programs in response to Fukushima, the WNA report notes that the global situation for energy supply and demand remains effectively unchanged. Prospects for new nuclear facilities remain strong in China, India, South Korea, and the United Kingdom, and developments in the United States, China, India, and Russia will remain particularly crucial in determining nuclear's overall role in global electricity supply.

Uranium does not trade on an open market like other commodities. Buyers (states or utilities) and sellers (states or mining companies) negotiate contracts privately and confidentially. Spot uranium prices—usually representing less than 20 percent of supply—are published by the independent market consultants Ux Consulting and TradeTech (e.g., Figure 3.22). Most trade is by 3- to 15-year term contracts with producers selling directly to utilities, although the price in these contracts is often related to the spot price at the time of delivery.

Presently, about 435 reactors with a combined capacity of over 370 GWe require 65,500 tU (77,000 tonnes U_3O_8). Each GWe of increased capacity requires 400 to 600 tU for the first fuel load, followed by about 200 tU per year. The capacity is growing slowly, and the reactors are being run more efficiently. Also, many utilities are increasing the initial enrichment of their fuel (e.g., from 3.3 percent to more than 4.0 percent ^{235}U), and then burning it longer or harder to have only 0.5 percent ^{235}U left in the spent fuel (instead of 0.8 percent or more). As a consequence of increased efficiency, over the 20 years from 1970 there was a 25 percent reduction in uranium demand per kilowatt-hour output in Europe.

FINDINGS AND KEY CONCEPTS

The committee's analysis of the distribution of uranium deposits in Virginia and worldwide, and uranium markets and reserves, has produced the following findings:

Uranium deposits are formed by a wide variety of geological processes and in a wide range of geological environments. ***Of the localities in Virginia where existing exploration data indicate that there are significant uranium occurrences, predominantly in the Blue Ridge and Piedmont geological terrains, only the deposits at Coles Hill in Pittsylvania County appear to be potentially economically viable at present.*** The resources and grades of the Coles Hill deposits appear comparable to deposits that are being mined elsewhere in the world.

Because of their geological characteristics, none of the known uranium occurrences in Virginia would be suitable for the in situ leaching/in situ recovery (ISL/ISR) uranium mining/processing technique. ISL/ISR mining requires specific hydrological and geological characteristics, with porous mineral-bearing rocks enclosed by relatively impermeable surfaces.

In 2008, uranium was produced in 20 countries; however, more than 92 percent of the world's uranium production came from only eight countries (Kazakhstan, Canada, Australia, Namibia, Niger, Russia, Uzbekistan, and the United States).

In general, uranium price trends since the early 1980s have closely tracked oil price trends. The Chernobyl (Ukraine) nuclear accident in 1986 did not have a significant impact on uranium prices, and it is too early to know the long-term uranium demand and price effects of the Fukushima (Japan) accident.

Existing known identified resources of uranium worldwide, based on present-day reactor technologies and assuming that the resources are developed, are sufficient to last for more than 50 years at today's rate of usage.

4

Uranium Mining, Processing, and Reclamation

Key Points

- The choice of mining methods and processing parameters for uranium recovery depends on multiple factors that are primarily associated with the geological and geotechnical characteristics of a uranium deposit—its mineralogy and rock type, as well as a range of other factors.
- Uranium recovery from ores is primarily a hydrometallurgical process using chemical processes with industrial chemicals, with a lesser dependence on physical processes such as crushing and grinding.
- Mine design—whether open-pit or underground—requires detailed engineering planning that would include pit and rock stability considerations, as well as ventilation design to account for the presence of radon and other respiratory hazards.
- With the ore grades expected in Virginia, many of the technical aspects of mining for uranium would be essentially the same as those applying to other hard-rock mining operations. However, uranium mining and processing add another dimension of risk because of the potential for exposure to elevated concentrations of radionuclides.

- A complete life-cycle analysis is an essential component of planning for the exploitation of a uranium deposit—from exploration, through engineering and design, to startup, operations, reclamation, and finally to decommissioning leading to final closure and postclosure monitoring.

This chapter outlines the basic steps involved in mining, processing, and reclamation that might be suitable for uranium ore deposits in the Commonwealth of Virginia. For uranium ore deposits, the choice of mining methods and processing options is very deposit-specific and dependent on many variables such as the quality and quantity of the ore, the shape and depth of the ore deposit, site-specific environmental conditions, and a range of other factors. Accordingly, the description of how uranium mining is undertaken in this report is generalized and at a high level.

Open-pit mining and underground mining are the two types of mining that would be used to exploit uranium deposits in Virginia. These mining techniques can be used individually or combined; for example, many mines start as open-pit operations and continue as underground operations to follow a deposit deeper below the surface. This chapter presents a short overview of both mining methods, and the considerations involved in using them. A short description of the in situ leaching/in situ recovery (ISL/ISR) uranium mining technique and other uranium mining techniques are included for completeness, even though, based on current knowledge of known uranium occurrences in Virginia, ISL/ISR is unlikely to be applicable.

After the uranium ore is removed from the ground, it must be treated at a hydrometallurgical processing facility to remove impurities and produce yellowcake. The specific type of hydrometallurgical process is also deposit-specific, dependent not only on the nature of the uranium mineral but also on the nature of the host rock as well as environmental, safety, and economic factors. Waste rock handling, tailings disposal, and final reclamation and closure are also discussed in this chapter because they are critical parts of a mine's life cycle.

One overarching consideration throughout the entire mining, processing, reclamation, and long-term stewardship process is the need for meaningful and timely public participation throughout the life cycle of a mining project, beginning at the earliest stages of project planning. This requires creating an environment in which the public is both informed about, and can comment upon, any decisions made that could affect their community (see additional discussion in Chapter 7).

URANIUM MINING METHODS

Based on the current understanding of uranium deposits in the Commonwealth of Virginia, extraction of uranium ore would use open-pit mining, or underground mining, or a combination of both (Figure 4.1). These general terms incorporate a large variety of design possibilities—there are as many methods of mining uranium as there are orebody sizes, shapes, and mineral constituents. The orebody size, location, orientation, rock quality, and the distribution of the valued minerals in it—along with site location and infrastructure—all play a part in the selection of the mining method and the overall plan for developing an orebody. Mines may range in size from very small underground operations, with considerably less than 100 tons of production per day, to large open-pits that move hundreds of thousands of tons of ore and waste per day. The descriptions of uranium occurrences in Virginia contained in the previous chapter indicate that most potential deposits will likely be hosted in a hard-rock setting, although geopolitical and market factors may in time enable uranium production as a byproduct of heavy mineral sand mining.

Underground Mining

Site-specific conditions, such as the depth of the ore deposit, its shape, surrounding geological conditions, and other factors, could result in the selection of an underground mining technique. In that case, the primary opening into an underground mine to provide access for people, materials, and equipment and to enable the ore to be brought to surface can be a shaft sunk vertically or on an "incline"; a "decline," which is a ramp driven into the earth usually in a spiral fashion; or an "adit," which is a horizontal opening driven into the side of a hill or mountain (Figure 4.1).

Both vertical and inclined shafts must be equipped with hoists and headframes, which are the structures at the top of the shafts that enclose and operate the hoists used for transporting ore and mine personnel (Figure 4.2). Ramps usually spiral downward so that rubber-tired mobile equipment will have access to the mine. In some cases, ramps are driven in a straight line to accommodate conveyor belts. Horizontal or level mine workings are referred to as "crosscuts" and "drifts"; vertical access workings are referred to as "raises" or "winzes."

Generally, orebodies are either vein type, massive, or tabular in shape, and both the shape and ore thickness influence the mining method used. Vein-type orebodies usually dip steeply, and this steepness can be used during mining with the ore being allowed to fall to lower levels to an extraction accessway (Figure 4.3). Uranium orebodies are often narrow and irregular. The strength of the ore material and the surrounding host rocks, as well as the ore grade and the distribution of the ore, influences the ore removal method. Mined openings may be either supported or self-supported. Some supported openings are held up

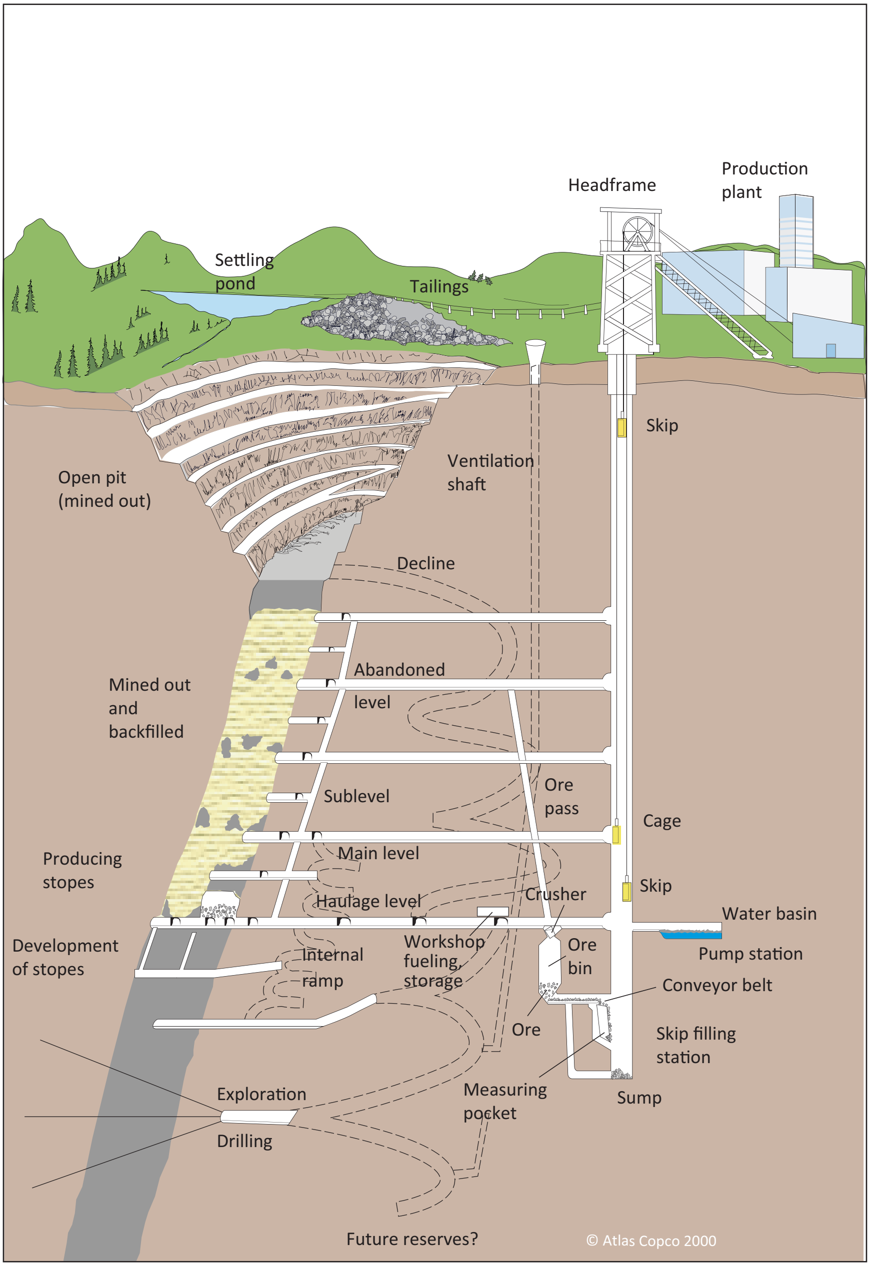

FIGURE 4.1 Components of a combined open-pit and underground mine. SOURCE: Modified; courtesy of Atlas Copco, Underground Rock Excavation Division.

FIGURE 4.2 Underground mine headframe and hoist room. SOURCE: Photograph courtesy Richard Cummins/SuperStock.

by backfill, that is, waste rock or aggregate placed in the openings shortly after they are mined out. Others are held up by timber, metal supports, concrete, rock bolts, or a combination of methods. The different techniques for underground mining have very specific names—cut and fill, drift and fill, shrinkage stoping, and block caving—and they are described below in very general terms based largely on ILO (2006):

Cut and fill mining is used in steeply dipping or irregular ore zones, where the mineral deposit is contained in a rock mass with good to moderate stability. Cut and fill mining removes the ore in horizontal slices starting from a bottom cut and advances upward, allowing the stope boundaries to be adjusted to follow irregular mineralization. This permits high-grade sections to be mined selectively, leaving low-grade ore in place. Access to the ore zone is by "ramping down" from a crosscut, and then holes are drilled in the rock face followed by blasting with explosives. After the ore is removed from the "cut," the resulting space is backfilled with waste rock or tailings, but with enough space left open to mine the next slice. Although cut and fill mining is relatively expensive, it minimizes ore loss and ore dilution.

Drift and fill mining is similar to cut and fill, but is used where the ore zone is too wide for a single cut. As with cut and fill mining, ore is removed after

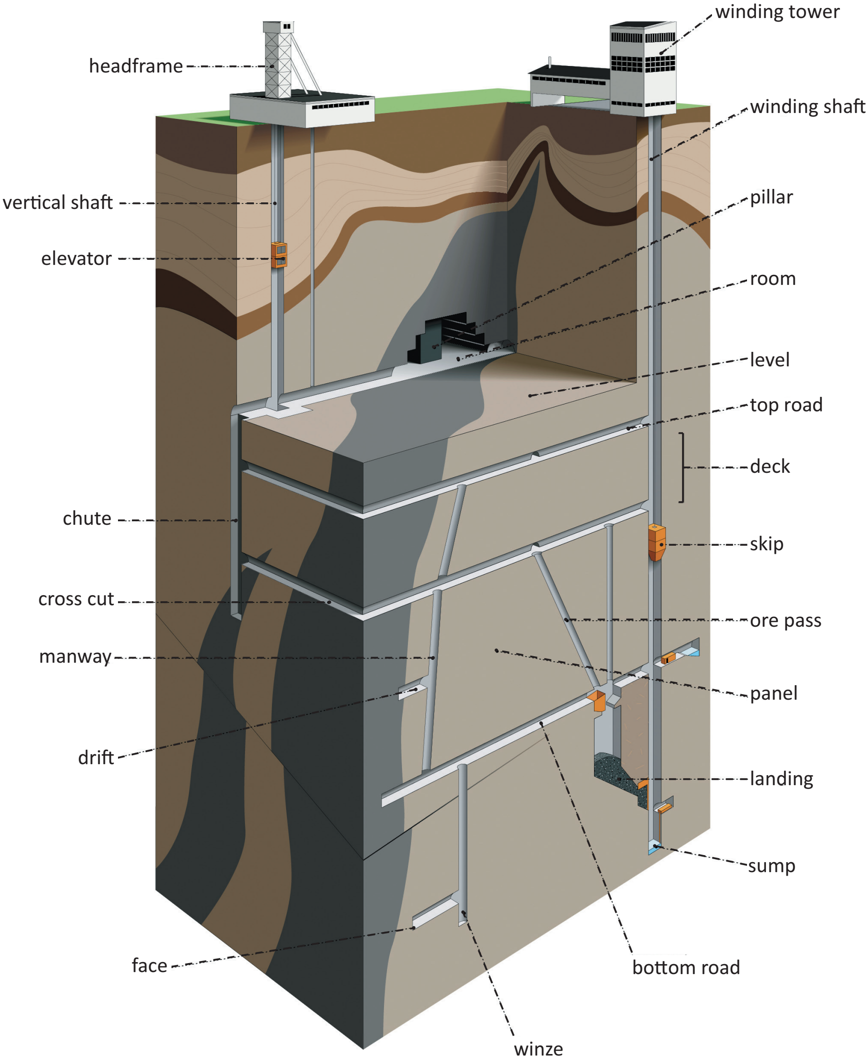

FIGURE 4.3 Underground mine with vertical shaft. SOURCE: Reproduced with the permission of QA International (http://www.qa-international.com from the book, "The Visual Dictionary" ©QA International 2003. All rights reserved).

blasting, and the resulting space is packed with fill material. With drift and fill mining, after completion of the first drift, a second drift is driven adjacent to the first. Additional drifts are developed until the ore zone is mined out to its full width, after which a second cut is started on top of the first cut.

Shrinkage stoping is a mining method that can be used for steeply dipping orebodies. Ore is extracted in horizontal slices, starting at the stope bottoms and advancing upward. Most of the blasted rock remains in the stope to provide a working platform for the miner drilling holes in the roof, and and it also serves to keep the stope walls stable. Because blasting increases the volume of the rock by about 60 percent, some 40 percent of the ore is drawn at the bottom during stoping in order to maintain a working space between the top of the blasted rock and the roof. The remaining ore is removed after blasting has reached the upper limit of the stope. Shrinkage stoping allows mining that is very selective, but one disadvantage is that there is a delayed return on capital investment because most of the ore stays underground until mining of the stope is completed.

Room and pillar mining is commonly done in flat or gently dipping orebodies. Room and pillar mining accesses an orebody by horizontal drilling advancing along a multifaced front, forming empty rooms behind the producing front. "Pillars" of rock are left between the rooms for support to keep the roof from caving. The usual result is a regular pattern of rooms and pillars, with their relative size representing a compromise between maintaining the stability of the rock mass and extracting as much of the ore as possible. In some room and pillar mines, once the rooms are mined out the pillars can be mined, starting at the farthest point, allowing the roof to collapse. This allows the ore contained in the pillars to be accessed.

Block caving is a large-scale mining method that is used to mine massive orebodies with specific characteristics that enable gravity to do part of the work. Preparation for block caving requires long-range planning and extensive initial development involving a complex system of excavations beneath the orebody. An "undercut" is mined under the orebody, and cavities are excavated to serve as repositories for caving rock to be collected. The orebody is drilled and blasted above the undercut, and ore is removed through the accessway. Because of the characteristics of the orebody, material above the first blast area falls into the collection areas. As ore is removed from the collection areas, subsequent caving provides steady availability of ore. Extensive rock bolting and concrete lining are required to keep the openings intact, and if caving stops and removal of ore continues, a large void may form that can have the potential for a sudden and massive collapse.

Ground Control in Underground Mining

Ground control—the prevention of rock collapse into a mined cavity—is an integral part of mine design to ensure a safe underground working operation.

Ground control design requires consideration of many factors, such as rock type, groundwater inflow, geological features, deposit shape and size, and others. Ground control may be as simple as leaving adequate support columns during the mining operation, or may involve more complex systems that use cemented backfill to infill voids. Methods also include the use of "rock bolting" and screens for stability, and shotcrete (i.e., a spray-on cement mixture) may be used to stabilize loose rock.

Ventilation in Underground Mining

Ventilation is a critical consideration for all underground mining. Adequate ventilation is required to provide fresh air to miners and to reduce exposure to gases, products of combustion, dusts (including siliceous material), heat and humidity, radioactive gases and solids, and diesel gases and particulate matter. For many hazardous components, ventilation is used to first dilute contaminants to a safe level, and then to remove them. The most common method for ventilation in the subsurface is by airflow from the surface produced by large fans. Underground booster fans can also be used to ventilate specific areas of a mine (e.g., Figure 4.4).

The design of a major underground ventilation and environmental control system is a complex undertaking (Figure 4.5). It requires a systems engineering approach that encompasses the entire mining process, to ensure that the consequences of changes in the mining techniques and size of the mine, and other factors, are accounted for in the control system design and operation.

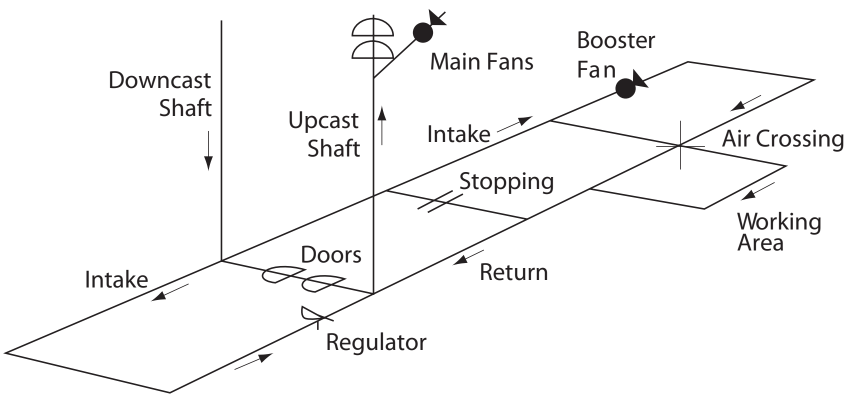

FIGURE 4.4 Schematic diagram showing a simple mine ventilation system. SOURCE: McPherson (1993); with permission from Springer Science and Business Media.

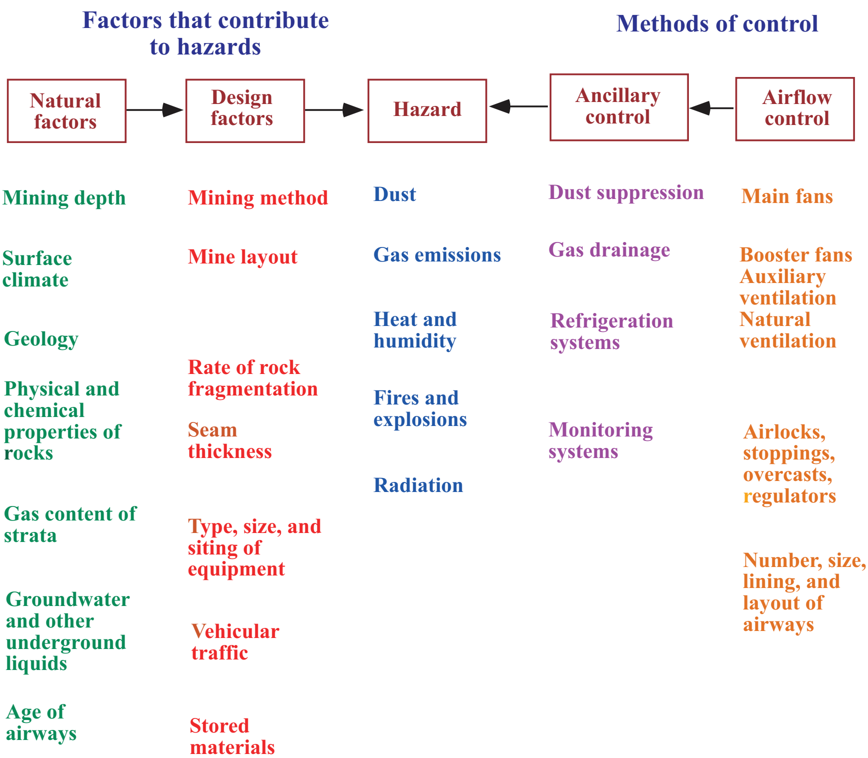

FIGURE 4.5 Multiple factors interacting in the creation and control of hazards in a subsurface environment. SOURCE: McPherson (1993); with permission from Springer Science and Business Media.

Open-Pit Mining

Compared with underground mining, an open-pit mine is usually less expensive. Unlike underground mining, equipment size is not restricted by the size of the opening to the mine and consequently open-pit mining can take advantage of economies of scale, using larger and more powerful shovels and trucks. Ore production is generally faster in open-pit mines, and lower costs per ton for the mined ore means that lower grades of ore can be mined economically. Open-pit mines do not require the extensive mine ventilation of underground mines, because generally there is sufficient air movement without ventilation equipment. Air monitoring for radon is usually carried out in case there is an atmospheric air inversion; however, these are usually short-lived, and mine operations are reduced in these instances. Air inversions may also be relevant for other exposures, for example, diesel vapors and particulates.

Open-pit mining is appropriate when the ore is near the surface, particularly if the ore deposit is relatively large and there is little overburden. There are several important design considerations for open-pit mines. First, the open-pit walls need to be constructed and angled so that they are strong enough to support a safe slope. Second, the depth to the ore will dictate how much waste overburden will need to be mined before production can begin. And third, the size of the first "bench" of any open-pit mine (Figure 4.6) must be planned carefully, as each successive bench will be smaller than the last one and, consequently, the dimensions of the initial bench will dictate the depth of the final open-pit.

The stripping ratio—the ratio of the amount of waste rock that has to be mined to the amount of ore mined—is a critical element for deciding the economic feasibility of exploiting a particular ore deposit with open-pit or underground mining. In most cases, this stripping ratio is high for the first bench, and decreases steadily for each successive bench. Obviously, an open-pit mine will only be economically feasible if the cost of mining the waste rock does not exceed the value of the ore.

Ore Recovery in Underground and Open-Pit Mining

Ore recovery involves a number of steps that are common to both open-pit and underground mining. The first step is to drill a pattern of small holes in the rock and the ore using electric or compressed-air hydraulic drill "jumbos."

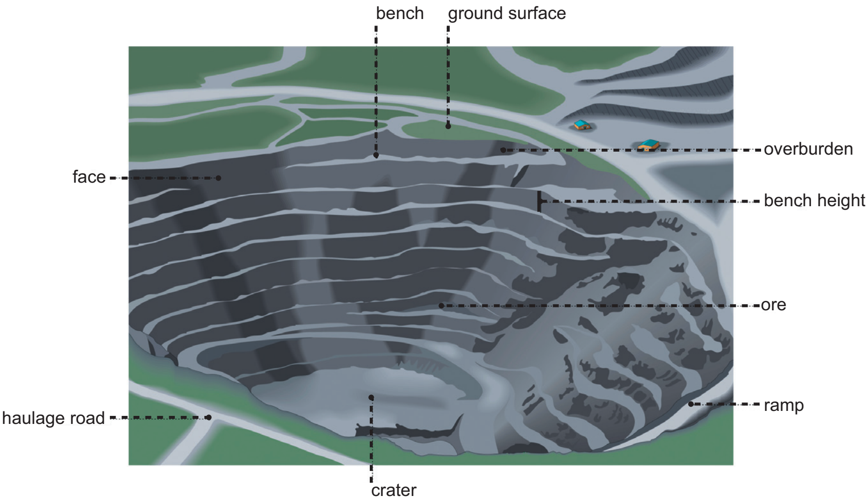

FIGURE 4.6 Typical open-pit mine structure. SOURCE: Reproduced with the permission of QA International (http://www.qa-international.com from the book, "The Visual Dictionary" ©QA International 2003. All rights reserved).

Explosives are loaded into the holes, and then detonated to break the rock. Commonly, nitroglycerine dynamites and ANFO (i.e., a mixture of ammonium nitrate fertilizer and fuel oil) are used as blasting agents. The blast is initiated by a high explosive blasting cap, usually with a primer.

Once the ore has been fragmented by blasting, and a suitable time interval has elapsed to allow safe reentry based on explosive gas dissipation, the ore is loaded into either trucks or rail cars to be transported to the processing area. In some cases, initial ore processing (often crushing) occurs underground or in the open-pit, followed by transportation for further processing via a conveyer belt system. After an underground area has been mined out, it is often necessary to backfill it with some waste material—this can occur immediately, or it can be delayed until the stope is completely mined out.

For safety reasons, large blasts in underground mines are usually set off electrically from the surface once all underground workers have reached the surface of the mine, usually at the end of a work shift. This precaution also limits exposure to the dust and fumes caused by a blast, because the ventilation system can flush the underground atmosphere before the next shift goes underground.

URANIUM PROCESSING METHODS

A hydrometallurgical process is used to produce uranium from uranium ore, using chemicals and solutions to extract the uranium from the ore matrix. The process is complete when the final uranium product, known as yellowcake, is produced in a sufficient high purity (typically 75 to 85 percent U_3O_8) so that it can be used in the remainder of the nuclear fuel production cycle.

There are four major process routes for uranium processing—conventional agitation leach, recovery as a byproduct, heap leaching, and ISL/ISR. This section provides an overview of these options, with emphasis on the conventional agitated leach process. In situ recovery is briefly discussed for the sake of completeness, but is not evaluated in detail because, as noted previously, it is unlikely to be appropriate for use in Virginia. Also for completeness, this section will briefly describe byproduct recovery.

A simplified schematic for uranium processing is shown in Figure 4.7, outlining the main unit processes required to produce the final high-purity uranium concentrate. There are variations within each unit process as required by the specific uranium ore being processed and the availability of specific chemicals and equipment.

Process Choice

Although the steps for recovery of uranium from ore can be shown simply (Figure 4.7), the actual choice of the final processes is complex and requires careful advance planning, analysis, and design. As with all decisions about the

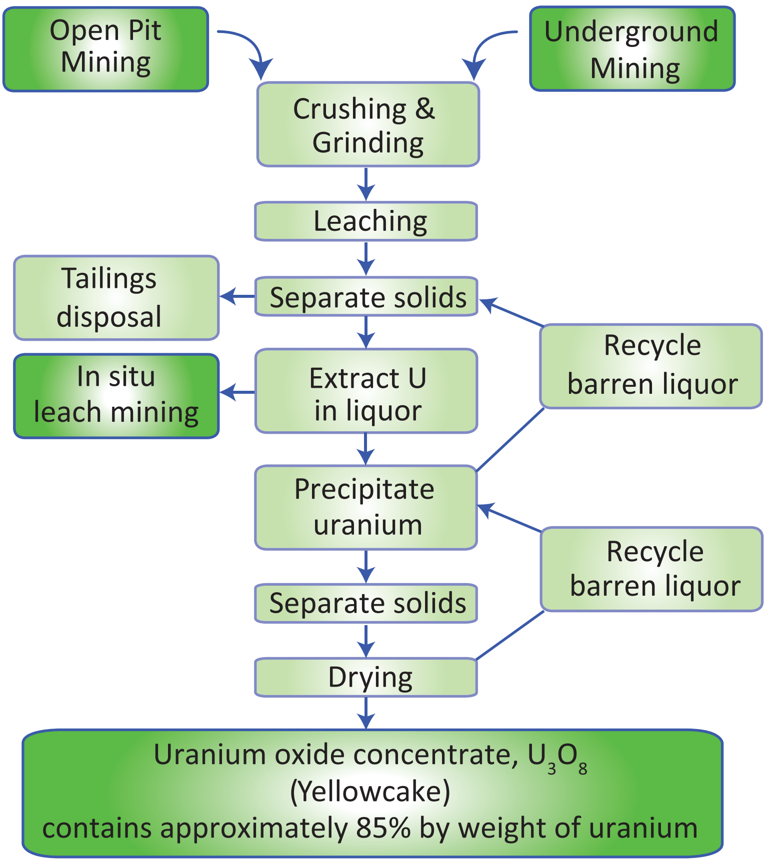

FIGURE 4.7 Uranium processing flow diagram showing the unit process steps, from ore produced by an open-pit or underground mine through to yellowcake production. SOURCE: WNA (2010b).

suitability of a particular ore deposit for mining suitability, a range of economic, social, and environmental issues are critical. The following primary considerations dictate process choice (El-Ansary and Schnell, 2010):

- Mining method
- Type of deposit
- Size of deposit
- Mineralogy of the ore
- Uranium grade
- Geographical location

- Climate
- Required production capacity
- Regulations and permitting
- Workforce availability and qualifications
- Deposit and country history
- Commodity volatility
- Capital cost
- Operating cost
- Schedule

Extensive planning, testing, and analysis of the ore and the surrounding rock are required as the first stage in process selection; in general, the type of ore—whether low or high grade, or whether it is a simple or complex mineralogy—can provide a first-order indication of processing options (Figure 4.8).

General Uranium Mineralogy

While the mining method for a particular uranium ore deposit will be determined by the type and size of the deposit, the choice of process will be primarily determined by the ore type and uranium mineralogy. For the ore, the host rock will have the highest influence on process choice except in the case of very-high-grade deposits (+5 percent U_3O_8); as noted in the previous chapter,

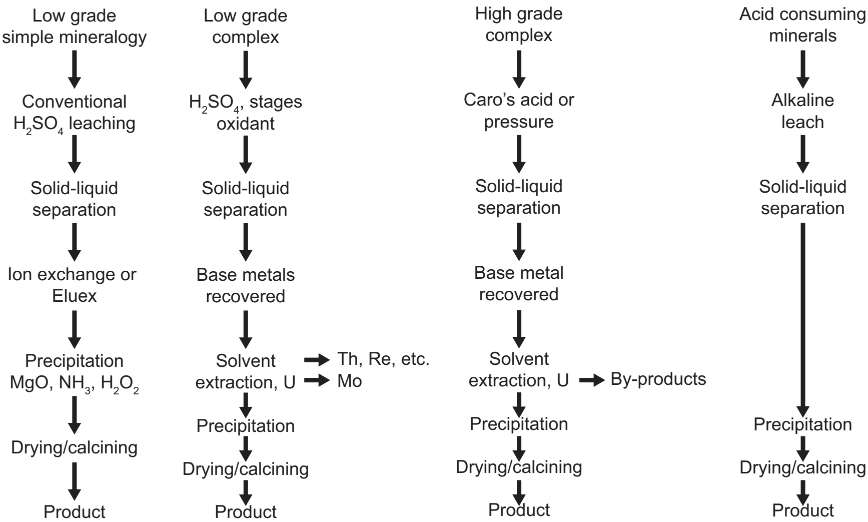

FIGURE 4.8 General overview of process selection based on ore characteristics. SOURCE: IAEA (1993); with permission of the International Atomic Energy Agency.

such high-grade deposits are not anticipated in Virginia. The host rock will be the primary determinant of the type of uranium leaching, either alkaline using a carbonate solution (sodium carbonate and sodium bicarbonate mixture) or acid (normally sulfuric acid; other acids are very rarely used). The quantity of acid or carbonates consumed, combined with the associated process costs, will determine the final process choice.

The nature of the host rocks plays a major part in the design of the sequence of processing steps—the flowsheet (Lunt et al., 2007). The presence of carbonate minerals in sufficient quantity to cause acid consumptions of greater than about 75 to 100 kg per tonne of ore leached is likely to be the deciding factor in favor of carbonate leaching. Generally, using an acid leaching process has advantages in terms of circuit simplicity and offering a greater range of purification options compared with alkaline leaching. However, each situation is evaluated on its own merits. In summary, the ultimate process route selection is influenced by the following (Lunt et al., 2007):

1. The concentration of uranium in the ore, with higher grade material being able to tolerate higher acid consumptions without having to contemplate alkaline leaching
2. The more rapid kinetics of the acid leach over carbonate digestion for the same ore type, which has ramifications on the leaching step and also on the degree of comminution (size reduction, usually by grinding or crushing) required, where acid leaching may not require such a fine grind
3. The presence of valuable byproducts in the ore and the ability of either flowsheet to recover these species economically
4. The price of the reagents themselves and the relative transportation costs
5. Choice of purification step in acid leaching, which is wider than that of alkaline leach circuits, the options for acid circuits including solid ion exchange (fixed bed, continuous countercurrent, resin-in-pulp, and the carousel) and SX (mixer-settler and pulsed column), and possibly combinations of IX/SX

Although ore or rock characteristics govern the overall leach process choice, between alkaline or acid leach, the specific uranium mineralogy must also be considered. Uranium occurs in a very large number of minerals because of its large ionic radius and its two valence states. Uranium minerals occurring in ore deposits (as described in Chapter 3) belong to the following general groups:

- Oxides, which represent by far the most common group of uranium minerals in ore deposits
- Silicates, which are second in importance, and occur in significant concentration in sandstone-hosted deposits
- Titanates, which mostly occur in some sodium-metasomatism related uranium deposits

- Vanadates, which essentially occur in calcretes
- Phosphates, carbonates, oxyhydroxides, arsenates, and other hexavalent uranium minerals, which generally occur as alteration products of other primary uranium minerals, and accordingly are called secondary uranium minerals.

Despite the very large range of uranium minerals that can occur, the most common uranium minerals exploited are uraninite and pitchblende, carnotite, coffinite, brannerite, and torbernite (Table 4.1).

As noted in Chapter 3, uranium in nature is generally found in the U^{4+} and U^{6+} oxidation states within the large variety of different uranium-containing mineral species. During uranium processing, the uranium is solubilized with the use of acids (normally sulfuric acid) or in an alkaline form (normally a carbonate or hydroxide form). The sulfate or carbonate requires the uranium to be in the U^{VI} oxidized state, which normally requires the addition of an oxidant in the leaching stage to improve overall metal content. The oxidants most commonly used are oxygen, hydrogen peroxide, sodium chlorate, or manganese dioxide.

Uranium Occurrence in Nature

Uranium in nature occurs over a very wide range of concentrations (Table 4.2). For a uranium occurrence to be considered as a feasible and economic ore deposit, it must be of sufficient size and be amenable to mining and processing. Worldwide, conventional uranium production is from ores that range from very

TABLE 4.1 Chemical Constituents of the Main Uranium Minerals

Primary Uranium Minerals	
Uraninite	$UO_{2.x}$
Pitchblende	$UO_{2.x}$ (x = 0.2-0.6)
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
Brannerite	(U, CA, Y, CE)(Ti, Fe)$_2$O$_6$
Davidite	(REE)(Y, U)(Ti, Fe^{3+})$_{20}$O$_{38}$
Thucholite	Thorium- and uranium-bearing organic material
Secondary Uranium Minerals	
Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 8\text{-}12\ H_2O$
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3\ H_2O$
Gummite	A mixture of uraninite and secondary uranium minerals of variable composition
Seleeite	$Mg(UO_2)_2(PO_4)_2 \cdot 10\ H_2O$
Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12\ H_2O$
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}8\ H_2O$
Uranocircite	$Ba(UO_2)_2(PO_4)_2 \cdot 8\text{-}10\ H_2O$
Uranophane	$Ca(UO_2)_2(HSiO_4)_2 \cdot 5\ H_2O$
Zeunerite	$Cu(UO_2)_2(AsO_4)_2 \cdot 8\text{-}10\ H_2O$

TABLE 4.2 Range of Uranium Concentrations in Ore Deposits and in Earth

Grade	Concentration (ppm U)
Very high-grade ore (Canada), 20% U	200,000
High-grade ore, 2% U	20,000
Low-grade ore, 0.1% U	1,000
Very low-grade ore (Namibia), 0.01% U	100
Granite	4-5
Sedimentary rock	2
Earth's continental crust (average)	2.8
Seawater	0.003

SOURCE: Schnell (2009).

high grade (20+ percent U_3O_8 in Canada) to very low grade (0.01 percent U_3O_8 in Namibia), with most world uranium deposits in the 0.05 to 0.5 percent uranium concentration range.

As noted in Chapter 3, it is highly unlikely that there will be deposits with grades in excess of 1.0 percent uranium in Virginia. In addition, contamination of ore deposits with selected toxic metals, in particular arsenic, is also not expected in Virginia. For uranium grades of 0.05 to 0.5 percent, a typical process would be conventional underground or open-pit mining followed by crushing, grinding, tank leaching, solid-liquid separation, a solution purification step, and final precipitation of a concentrate. In the 0.05 to 0.5 percent uranium grade range, there is limited requirement for special precautions—beyond standard engineering practice—except for general dust control, ventilation for radon emissions, and a minor amount of nonradon radiation protection. For higher-grade uranium ores, additional controls are required targeting gamma radiation, and ores with specific toxic metal contamination (in particular arsenic) require other types of control.

Ore Pretreatment or Beneficiation

A process step that may precede conventional agitation leaching and possible heap leaching is ore pretreatment, or "beneficiation," in order to reduce the quantity of ore that will require chemical treatment. Beneficiation involves separating some of the host rock from the uranium-bearing mineral. This type of beneficiation can result in lower capital and operating costs, and may be a relevant option for lower grade deposits such as those that are likely to occur in Virginia. Generally, very few operations have used flotation or beneficiation processes that concentrate the uranium mineral by removing gangue constituents, because the value of the uranium losses is commonly higher than processing the whole ore. Flotation, gravity separation and other beneficiation processes that separate the uranium minerals from the gangue are tested during project planning, and in

some cases economic benefits can be realized. This is possible because, in many deposits, the uranium mineralization is found in fissures or cracks within the rock, rather than being disseminated through the rock as is often the case with other metal mineralization.

Conventional Agitation Leach

Uranium is highly soluble as a sulfate in sulfuric acid, and as a carbonate in alkaline solution in the U^{6+} valence state. If it occurs in the U^{4+} state it must oxidized before becoming soluble; this is a two-step reaction, with a chemical oxidant first used to oxidize iron, for example, from the ferrous Fe^{2+} to the ferric Fe^{3+} state, and in turn the oxidized iron causes oxidation of the uranium from U^{4+} to U^{6+} (Merritt, 1971).

The use of an agitated leaching process is the most common type of uranium processing, and is the one most likely to be applied to deposits in Virginia. The choice between an acid leaching process or alkaline leaching process is dependent on the ore and gangue and the uranium mineralogy. Extensive testing, economic studies, and environmental considerations will decide the final process choices.

The first step in the agitated leaching process is to finely grind the ore (typically to about 300- to 500-micron size) in a water–slurry mixture. The ore slurry is thickened to a higher density (about 50 percent solids), and then forwarded to a series of stirred tanks where the leaching takes place. Acid and oxidants are added—for acid leaching, temperatures of 50°C to 60°C are used, whereas alkaline leaching requires a higher temperature of 90°C to 95°C. The tanks can be at normal atmospheric pressure or pressurized. Acid and a suitable oxidant (e.g., oxygen, hydrogen peroxide, sodium chlorate, or manganese dioxide) is added to oxidize U^{4+} to U^{6+}. The acid is the lixiviant—or liquid solution—that dissolves the metal in the U^{6+} sulfate form. Alternatively, a mixture of sodium carbonate and sodium bicarbonate can be used if the ore gangue has a high acid consumption. The choice of a carbonate or acid leaching route is based on the consumption of each chemical by the ore matrix or host rock, reagent availability, and environmental and economic considerations. The choice of oxidant is based on many of the same considerations as the choice of lixiviant.

In either acid or alkaline leaching, the ore slurry—with the uranium in solution—requires the separation of the solids from the uranium-containing liquid. This is commonly performed using filters (horizontal belt, pressure, or drum filters) or a series of thickeners or decanters. In both cases, the slurry is washed with acidified water for the acid leach process, or water only in the case of the alkaline leach option, in what is termed countercurrent decantation. The washed solids, now referred to as tailings, are generally neutralized with lime or other alkaline material if acid leaching of the ore was employed to extract the uranium. The tailings are then forwarded to a tailings impoundment facility for storage.

The clear liquid containing the uranium in solution is further purified using a solvent extraction or ion exchange technology. After uranium removal, the solution—known as "raffinate" or "barren solution"—is recycled back to the filters or decantation process. The concentrated, purified uranium solution (referred to as "pregnant solution" or "eluate") is advanced to a precipitation stage using hydrogen peroxide, magnesium oxide, or sodium hydroxide. The resultant uranium precipitate is then filtered or centrifuged, dried or calcined, and packaged into suitable drums for shipping. All processing plants maximize solution and reagent recycling to reduce cost and environmental effects. A typical conventional agitation leaching process is illustrated in Figure 4.9. The final yellowcake prod-

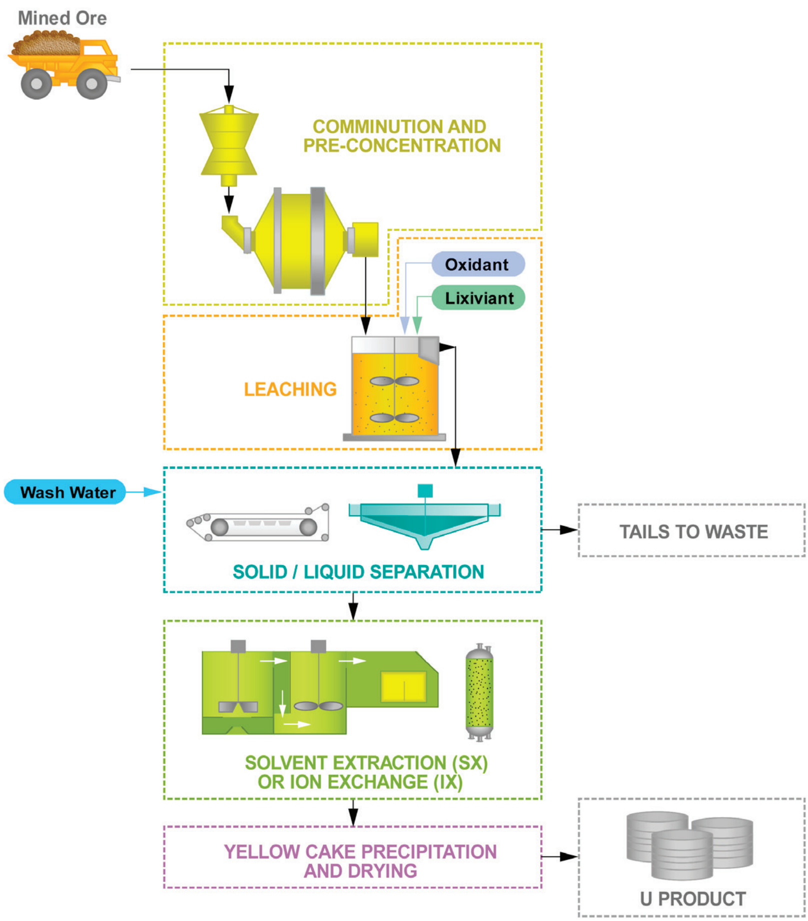

FIGURE 4.9 Typical conventional agitated leaching process. SOURCE: Courtesy of Zeyad El-Ansary, AMEC Minproc Ltd.

uct is normally packaged in an IP2-approved drum containing 400 to 500 kg of concentrate. All yellowcake product and uranium-containing material has strict accountability controls and is only shipped to other licensed facilities.

Although the specific uranium processing method that might be used for an ore deposit in Virginia would be dependent on the specific situation, some of the parameters that would need to be considered for a modern conventional agitated leaching operation, and a typical set of basic design criteria, are shown in Table 4.3.

Modern uranium processing operations have very strict mine-plant-product accounting practices to control the process and ensure an accurate accounting of recovery and production. Metallurgical accounting occurs daily, with a monthly balance and reconciliation, and is supported by a chemical laboratory that must be certified and have external check analysis systems.

In Situ Recovery (ISL or ISR)

In situ leaching (ISL), also known as solution mining, or in situ recovery (ISR) in North America, involves leaving the uranium ore in the ground, and recovering the uranium by dissolving it from the uranium-bearing minerals by injecting carbonated solution or mild acid and pumping the leached uranium in a pregnant solution to the surface where the metal can be recovered (Figure 4.10). Consequently, there is little surface disturbance and no tailings or waste rock generated. However, the orebody needs to be permeable to the liquids used and located so that the process does not contaminate groundwater away from the orebody (WNA, 2010a).

Uranium ISL uses the native groundwater in the orebody, which is fortified with a complexing agent, a mild alkaline solution (used in the United States) or weak sulfuric acid (used outside the United States), and in some cases the addition of an oxidant. It is then pumped through the underground orebody to recover the uranium by leaching. Once the pregnant solution is returned to the surface, the uranium is recovered in much the same way as in any other uranium processing plant.

The ISR method requires that the ore deposit rock structure be permeable (commonly sandstone) and have an underlying impermeable confining layer (such as a clay) beneath the mineralization. This method has been applied in the United States (e.g., in Wyoming and Texas), but as described in Chapter 3, the geological setting in Virginia is unlikely to be appropriate for this type of process.

Heap Leaching

Heap leaching occurs when ore containing uranium is piled in a heap and fluid is distributed over the surface to leach metal from the heap over a period of months. Heap leaching has been applied successfully for production of copper,

TABLE 4.3 Typical Uranium Mine and Processing Plant Design Criteria That Might Be Applicable to an Ore Deposit in Virginia

Item	Range or Alternative	Range or Alternative	Units
Deposit			
Resource tonnage	5 to 20		Million tons of ore
Resource grade	0.05 to 0.20		% U_3O_8
Uranium content	20 to 50		Million lbs U_3O_8
Ore depth from surface	Surface to 1,000		Feet
Deposit area	50 to 100		Acres
Mine	**Open-pit mine alternative**	**Underground mine alternative**	
Depth	Surface to 500	300 to 1,000	Feet
Open mine/strip ratio	3 to 10	0.5 to 2	Tons waste to tons ore
Underground dilution	5,000 to 50,000	1,000 to 20,000	Tons waste to tons ore
Daily mined tonnage	1,000 to 10,000	500 to 5,000	Tons ore plus tons waste per day
Daily ore mined			Tons per day
Plant	**Acid leaching alternative**	**Alkaline leaching alternative**	
Daily tons of ore	1,000 to 10,000	1,000 to 10,000	Tons per day
Leach recovery	90 to 95	80 to 85	%
Grind size	35 (0.02)	65 (0.01)	Mesh (inch)
Leach temperature	120 to 135	190 to 205	Degrees Fahrenheit
Leach time	8 to 12	48 to 96	Hours
Slurry solids	40 to 60	40 to 60	% solids
Acid consumption	80 to 200	—	Pounds per ton
Oxidant	O_2, H_2O_2, Na_2ClO_3	O_2 or air	
Carbonate concentration	—	30 to 50	Gram per liter
Carbonate consumption	—	5 to 10	Pounds per ton
Bicarbonate concentration	—	7 to 12	Gram per liter
Bicarbonate consumption	—	2 to 10	Pounds per ton
Purification	Solvent extraction or Ion exchange	Direct precipitation or ion exchange	
Precipitation	H_2O_2	NaOH and then H_2O_2	
Final product	UO_4 or U_3O_8	UO_4 or U_3O_8	
Tailings treatment	Lime neutralization	Wash tailings for solution recycle	

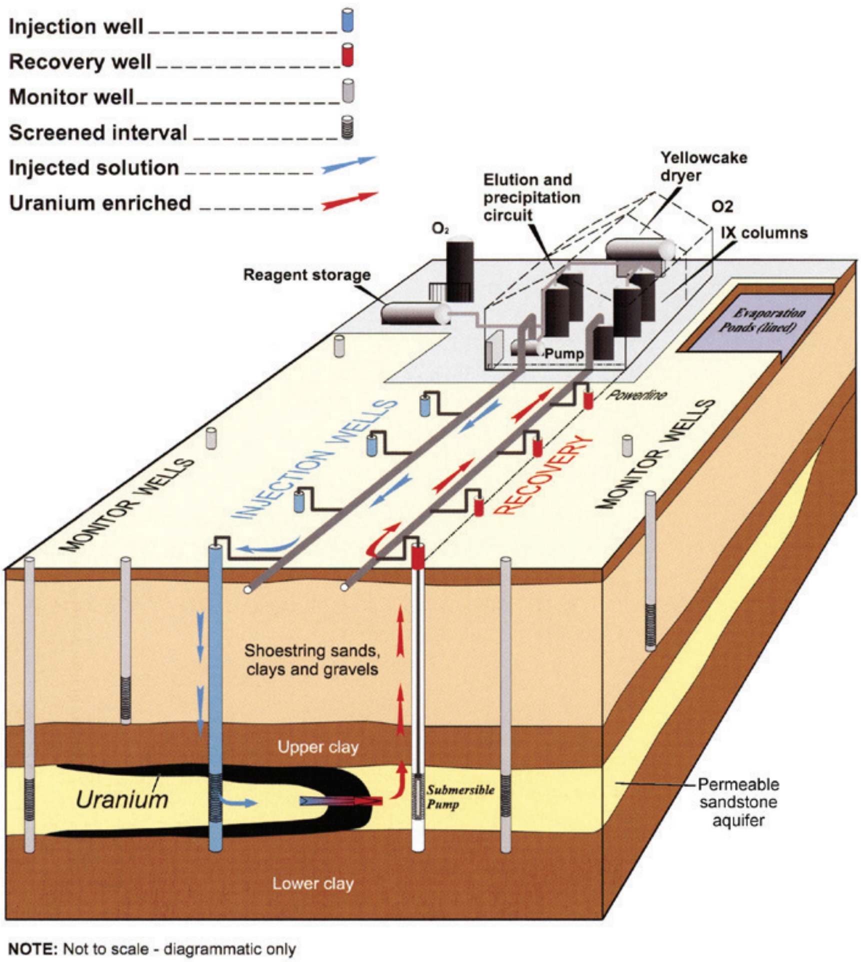

FIGURE 4.10 Typical ISR installation. SOURCE: With permission from Heathgate Resources Pty Ltd.

most notably in Chile and the western United States (Schnell, 1997), and for gold operations in South Dakota, Montana, Nevada, and many other parts of the world. Recovery of uranium by heap leaching is less common, with acid heap leaching used in Hungary (NEA/IAEA, 2000) and and alkaline heap leaching process used in Namibia (Schnell, 2010). Heap leaching today is applied to crushed ores, and modern heaps are designed to prevent ground contamination using a minimum of double containment, groundwater monitoring, and diversion channels. The advantage of heap leaching is that the ore does not need to be finely ground, water

consumption is low, and remediation is simplified, avoiding tailings impoundment. The leached residue can be returned to the mine or covered with suitable material in place. Heap leach is limited to ores with low clay content, and the process requires long leach times and has relatively low metal recovery.

Byproduct Uranium Recovery

Byproduct uranium recovery occurs when other metal production, such as gold, copper, or nickel, is the primary product and uranium is recovered as a minor byproduct. This may be done to recover uranium for its own sake, or undertaken when the uranium has to be removed for product purity or environmental reasons, for example, in the production of phosphoric acid fertilizer, or copper production such as with the Olympic Dam deposit in Australia.

Unconventional Resources

Uranium may be recovered from tailings from old uranium operations, or tailings from other metal operations. Generally speaking, these sources are currently not economically viable because of low concentrations and high processing costs, but they may have future production potential.

WATER TREATMENT

Virginia's environmental conditions make it almost certain that a mine—whether underground or open-pit—will be wet, and water will need to be removed and managed. Water removed from a mine or excess water that cannot be recycled within a processing plant must be treated to meet environmental requirements. Treatment will be dependent upon the uranium recovery process, chemicals used, and ore contaminants. Typically, treatment will be a multistep process that will neutralize the effluents, precipitate any metals, and diminish the uranium and radium content.

Water management within a mining project starts with a characterization of all potential water sources, possible usage, and possible contamination issues. This includes a site water balance analysis, including a plant water balance analysis, that assesses not just water flows and water quality but also identifies water recycle options. This water balance analysis would consider seasonal variations, and consider the use of cutoff berms, stormwater ponds, and possible evaporation ponds, all based on a probable-maximum-precipitation analysis with a suitable safety margin.

Water recovered from mining activities gets into the mine as groundwater, and this would either be discharged or used for plant operations. Contaminated mine water requires solids removal, either in settling basins or by use of filtration systems. In some cases, contaminated mine water may contain minor quantities

of metals that could require other technologies for treatment, for example, reverse osmosis or nanofiltration. After treatment, mine water is either discharged, recycled to plant operations, or sent for additional treatment.

Process effluents are internally recycled to minimize water usage and conserve process chemicals. Typical plant water usage will be on the order of 0.5-2.0 m^3 of water per ton of ore. Process or plant effluents require treatment to neutralize any chemicals, precipitate any dissolved metals, and precipitate radium. A multistep process is usually applied (e.g., Figure 4.11), first coagulating or precipitating heavy metals, neutralizing acids, or adjusting pH and then precipitating radium with barium chloride. The water treatment process can be followed by additional "clarification" or "polishing" steps using clarifiers, sand filters, and possibly reverse osmosis. The final selected treatment is dependent upon the plant

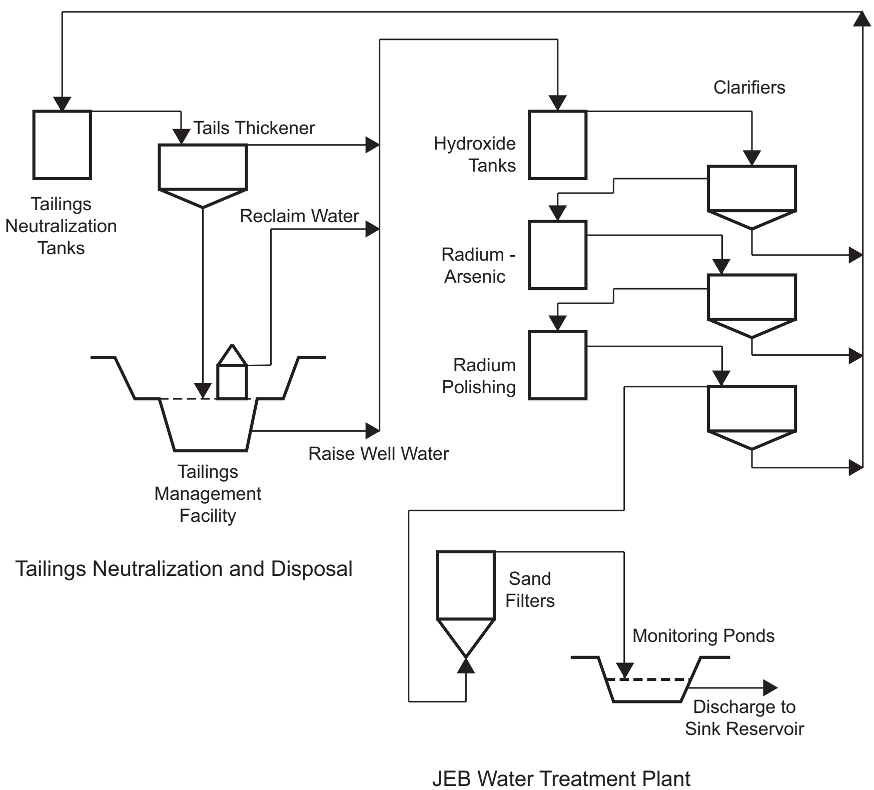

FIGURE 4.11 Example of multistage water treatment flowsheet showing treatment for metal content and radium and including pH adjustment with associated clarification as well as real-time monitoring of water quality before discharge. SOURCE: Schnell and Thiry (2007).

process, type of ore treated, and chemicals employed. In Canadian operations, for example, the final treated effluents are discharged into holding ponds, where they are analyzed to ensure that the treated effluents meet environmental objectives before release.

TAILINGS DISPOSAL

All ore mining produces waste rock that must be managed. This rock can be either waste that may produce acid mine drainage (AMD), due to the presence of sulfides, or it may be clean or stable waste that can be placed on the surface without special consideration. AMD waste is generally stored on an engineered pad to control water drainage, and is either returned to the mine as backfill or placed in an open containment pit at the end of mining. Such a containment pit may also have an engineered cover to prevent influx of water and oxygen to reduce the risk of acid mine water runoff.

The solid waste remaining after recovery of uranium in a processing plant are the tailings, consisting of everything that was in the ore except the extracted uranium. The main radioactive materials remaining are those from the uranium decay series, mainly thorium-230 and radium-226. Tailings are typically neutralized and thickened to reduce water content and then pumped to an impoundment facility. One concern for tailings impoundments is the potential for release of radon gas, and impoundments are monitored to ensure that radon does not pose a hazard. Radon can be controlled by limiting the amount of tailings exposed during operations by maintaining only small parts of an impoundment cell open at any one time, or by use of a water cover.

The characteristics of tailings impoundments have undergone many changes in recent decades. Historically, tailings were generally deposited in aboveground dam impoundments or in natural ground low points, with minimal treatment. In most cases, tailings are now impounded in purpose-built lined cells, placed in a mined-out pit, or sent to an engineered facility. Modern mines have tailings neutralization systems that use lime—together with other additives such as barium chloride—to stabilize radium content and prevent metal contaminants from causing environmental contamination.

The purpose-built lined pit or system of tailings cells has been adopted as the current practice in the United States. This is combined with a final cover to stabilize the tailings and prevent future contamination (Figure 4.12). For acid leach plants, all tailings need to be neutralized before disposal.

An alternative to the tailings cell design is to use in-pit disposal, where the tailings are placed in a designed open pit that allows the tailings to become less permeable than the surrounding rock, and a French drain prevents groundwater from entering the tailings mass (Figure 4.13). The tailings are placed subaqueous to prevent dust and to protect workers from potential radiation exposure. For final closure, the tailings mass is required to be below the surrounding ground

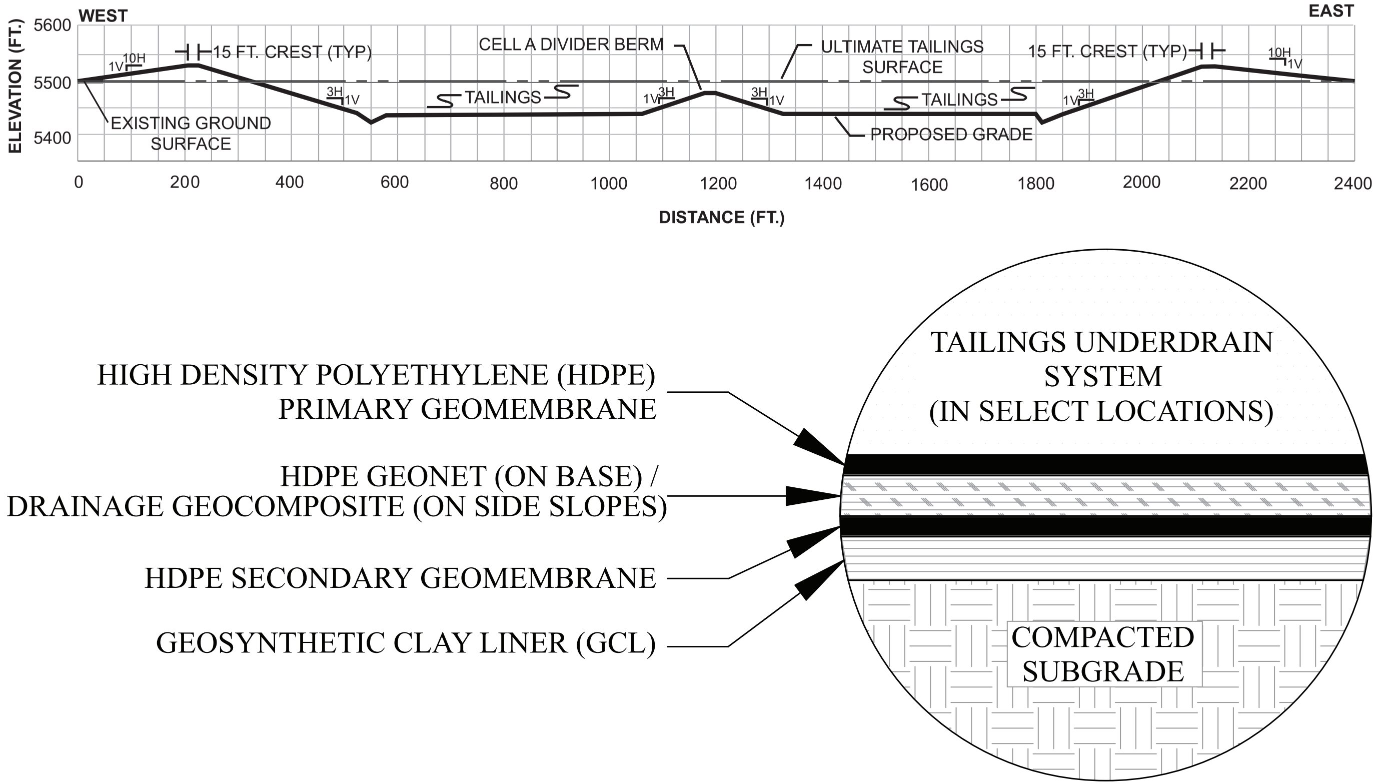

FIGURE 4.12 A purpose-built tailings impoundment facility was recently approved for the Piñon Ridge processing facility in Colorado: (A) overall tailings cell design, (B) cross section of the tailings liner system. SOURCE: Morrison et al. (2008).

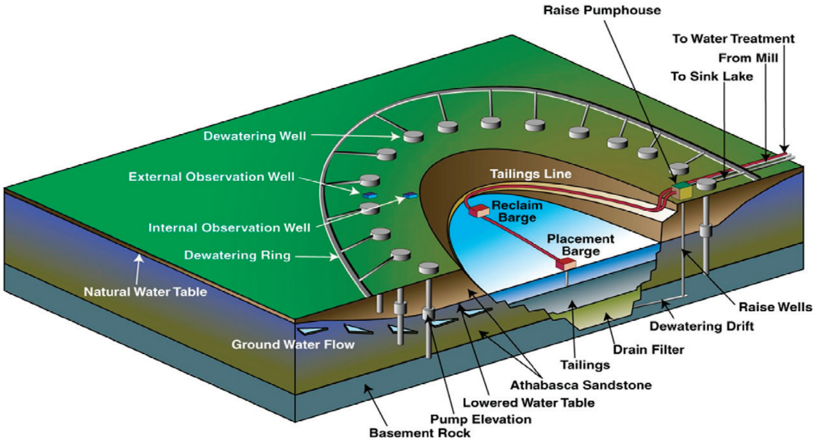

FIGURE 4.13 Schematic showing an in-pit tailings disposal system. SOURCE: AREVA Resources Canada, Inc.

level, and an engineered cover is installed to prevent contamination and stabilize the area.

RECLAMATION AND CLOSURE

Although reclamation and closure have always been considered during mine development, current practice has advanced to the point where the reclamation and closure plan is an important element for any mine's ultimate success. Reclamation and closure are planned during the earliest stages of the project, and encompass the initial gathering of comprehensive baseline environmental data, developing detailed cost of closure estimates, through to the actual implementation of the reclamation plan to ultimately trigger bond release (Feige, 2008). These plans consider all disturbances associated with the mine and processing plant areas. Closure activities may involve some postclosure water treatment where a treatment facility is required, and long-term sampling is undertaken.

Modern mine practice is to carry out continuous rehabilitation during the life of an operation. Appropriate reclamation and closure are guaranteed by a bond to ensure that sufficient resources are available should the operating company fail prior to final reclamation and closure. It is difficult to envision and describe all postclosure requirements, but modern practice is to review risks and assess opportunities to reduce final closure impacts early in the project design phase. Such impacts encompass not only technical and environmental issues, but also socioeconomic issues such as future site use.

FINDINGS AND KEY CONCEPTS

The committee's analysis of mining and processing activities that might apply if uranium mining and processing were to take place in Virginia has produced the following findings:

- ***The choice of mining techniques and processing parameters for uranium recovery depends on multiple factors that are primarily associated with the geological and geotechnical characteristics of a uranium deposit—its mineralogy and rock type, as well as a range of other factors.*** Additional parameters that require consideration are the location and depth of the deposit, whether the location is in a positive or negative water balance situation, as well as a range of environmental and socioeconomic factors. Consequently, a final design would require extensive site-specific analysis, and accordingly it is not possible at this stage to predict what specific type of uranium mining or processing might apply to ore deposits in Virginia.
- ***Uranium recovery from ores is primarily a hydrometallurgical process using chemical processes with industrial chemicals, with a lesser dependence on physical processes such as crushing and grinding.***
- ***Mine design—whether open-pit or underground—requires detailed engineering planning that would include pit and rock stability considerations, as well as ventilation design to account for the presence of radon and other respiratory hazards.***
- ***With the ore grades expected in Virginia, many of the technical aspects of mining for uranium would be essentially the same as those applying to other hard-rock mining operations. However, uranium mining and processing add another dimension of risk because of the potential for exposure to elevated concentrations of radionuclides.*** Hard-rock mining varies significantly from soft rock mining, such as coal or sand/gravel mining.
- ***A complete life-cycle analysis is an essential component of planning for the exploitation of a uranium deposit—from exploration, through engineering and design, to startup, operations, reclamation, and finally to decommissioning leading to final closure and postclosure monitoring.*** Each of these steps requires wide-ranging stakeholder interaction and communications.

5

Potential Human Health Effects of Uranium Mining, Processing, and Reclamation

Key Points

- Uranium mining and processing are associated with a wide range of potential adverse human health risks. Some of these risks arise out of aspects of uranium mining and processing specific to that enterprise, whereas other risks apply to the mining sector generally, and still others are linked more broadly to large-scale industrial or construction activities. These health risks typically are most relevant to individuals occupationally exposed in this industry, but certain exposures and their associated risks can extend via environmental pathways to the general population.
- Protracted exposure to radon decay products generally represents the greatest radiation-related health risk from uranium-related mining and processing operations. Radon's alpha-emitting radioactive decay products are strongly and causally linked to lung cancer in humans. Indeed, the populations in which this has been most clearly established are uranium miners that were occupationally exposed to radon.
- In 1987, the National Institute for Occupational Safety and Health (NIOSH) recognized that current occupational standards for radon exposure in the United States do not provide adequate protection for workers at risk of lung cancer from protracted radon

decay exposure, recommending that the occupational exposure limit for radon decay products should be reduced substantially. To date, this recommendation by NIOSH has not been incorporated into an enforceable standard by the Department of Labor's Mine Safety and Health Administration or the Occupational Safety and Health Administration.

- Radon and its alpha-emitting radioactive decay products are generally the most important, but are not the only radionuclides of health concern associated with uranium mining and processing. Workers are also at risk from exposure to other radionuclides, including uranium itself, which undergo radioactive decay by alpha, beta, or gamma emission. In particular, radium-226 and its decay products (e.g., bismuth-214 and lead-214) present alpha and gamma radiation hazards to uranium miners and processors.
- Radiation exposures to the general population resulting from off-site releases of radionuclides (e.g., airborne radon decay products, airborne thorium-230 (^{230}Th) or radium-226 (^{226}Ra) particles, ^{226}Ra in water supplies) present some risk. The potential for adverse health effects increases if there are uncontrolled releases as a result of extreme events (e.g., floods, fires, earthquakes) or human error. The potential for adverse health effects related to releases of radionuclides is directly related to the population density near the mine or processing facility.
- Internal exposure to radioactive materials during uranium mining and processing can take place through inhalation, ingestion, or through a cut in the skin. External radiation exposure (e.g., exposure to beta, gamma, and to a lesser extent, alpha radiation) can also present a health risk.
- Because ^{230}Th and ^{226}Ra are present in mine tailings, these radionuclides and their decay products can—if not controlled adequately—contaminate the local environment under certain conditions, in particular by seeping into water sources and thereby increasing radionuclide concentrations. This, in turn, can lead to a risk of cancer from drinking water (e.g., cancer of the bone) that is higher than the risk of cancer that would have existed had there been no radionuclide release from tailings.
- A large proportion of the epidemiological studies performed in the United States, exploring adverse health effects from potential off-site radionuclide releases from uranium mining and processing facilities, have lacked the ability to evaluate causal relationships

(e.g., to test study hypotheses) because of their ecological study design.

- The decay products of uranium (e.g., ^{230}Th, ^{226}Ra) provide a constant source of radiation in uranium tailings for thousands of years, substantially outlasting the current U.S. regulations for oversight of processing facility tailings.
- Radionuclides are not the only uranium mining- and processing-associated occupational exposures with potential adverse human health effects; two other notable inhalation risks are posed by silica dust and diesel exhaust. Neither of these is specific to uranium mining, but both have been prevalent historically in the uranium mining and processing industry. Of particular importance is the body of evidence from occupational studies showing that both silica and diesel exhaust exposure increase the risk of lung cancer, the main risk also associated with radon decay product exposure. To the extent that cigarette smoking poses further risk in absolute terms, there is potential for increased disease, including combined effects that are more than just additive.
- Although uranium mining-specific injury data for the United States were not available for review, work-related physical trauma risk (including electrical injury) is particularly high in the mining sector overall and this could be anticipated to also apply to uranium mining. In addition, hearing loss has been a major problem in the mining sector generally, and based on limited data from overseas studies, may also be a problem for uranium mining.
- A number of other exposures associated with uranium mining or processing, including waste management, also could carry the potential for adverse human health effects, although in many cases the detailed studies that might better elucidate such risks are not available.
- Assessing the potential risks of multiple combined exposures from uranium mining and processing activities is not possible in practical terms, even though the example of multiple potential lung carcinogen exposures in uranium mining and processing underscores that this is more than a theoretical concern.

Many of the findings related to occupational exposures and adverse health outcomes presented in this chapter are based on studies of uranium and hard-rock miners (e.g., worker-based radon studies) for periods of disease risk when the magnitude of the exposures was much greater than the exposures reported at most mines and processing facilities in North America today. Nevertheless, although current exposures are generally much lower, contemporary uranium workers and processors in the United States continue to express work-related health concerns. For example, in 2008 the National Institute of Occupational Safety and Health (NIOSH) organized stakeholder meetings that included uranium miners and processors in Wyoming, Texas, Colorado, and Utah. The stakeholders expressed numerous health-related concerns, including concerns about exposure to alpha radiation via inhalation or ingestion of dust particles containing radon decay products, exposure to both radiation and particulate uranium via inhalation, ingestion and inhalation of ore dust, and exposure to diesel particulate matter (Miller et al., 2008).

This chapter describes some of the major human health effects related to occupational and public (i.e., off-site) health and safety as they pertain to uranium mining, processing, and reclamation in the Commonwealth of Virginia. Specifically, the chapter discusses the well-documented human health effects arising from the radioactive constituents of uranium mining that are of primary health concern, including uranium and its decay products (e.g., radium, radon). In addition, the chapter provides an overview of other, nonradioactive hazards related to mining and processing. This includes both a group of major exposures (i.e., silica, diesel, and physical exposure hazards) as well as a group of miscellaneous potential hazards related to mining in general and to uranium processing in particular. Epidemiological and other human health data derived from previous studies of uranium mining and processing were examined, as well as other relevant biomedical data pertaining to the potential exposures of interest.

It was not the Committee's charge to develop a quantitative risk assessment, or to characterize uranium mining- and processing-associated risks scaled and ranked against various occupational and nonoccupational hazards (such as risks quantified for activities such as travel, hobby activities, or military service). Although such information might be of interest to various stakeholders in Virginia, and would undoubtedly be required for a site-specific analysis, it is beyond the resources, scope, and capabilities of the Committee as constituted to carry out the extensive research that would be required to undertake such a Virginia-wide analysis.

RADIONUCLIDE-RELATED HEALTH HAZARDS

For many of its aspects, the potential adverse health effects associated with uranium mining are no different than the risks identified in other types of non-radiation-related mining activities (Laurence, 2011). Uranium mining, however,

adds another dimension of risk because of the potential for exposure to elevated concentrations of radionuclides. Internal exposure to radioactive materials during uranium mining and processing can take place through inhalation, ingestion, or absorption through an open cut or wound. External radiation exposure from beta particles or gamma rays can also present a health risk.

Radiation typically encountered in uranium mining or processing facility operations includes alpha (α), beta (β), and gamma (γ) radiation. All three are types of ionizing radiation—energy in the form of particles or waves that has sufficient force to remove electrons from atoms. Alpha particles consist of two neutrons and two protons, travel only a few centimeters in air, and can cause a high density of ionizations along their path. In some cases, alpha particles can penetrate the dead layer of skin. If radionuclides that decay by alpha emission (e.g., polonium-218, polonium-214) are inhaled, they have the potential to impart a significant dose to the pulmonary epithelium. The dose of alpha energy delivered by an alpha particle to the DNA in a cell in the respiratory epithelium is fixed and not dependent on concentration or duration of exposure. Although alpha particles can travel only a short distance, they impart a much greater effective dose than beta particles or gamma rays (NRC, 1988, 2008b). The high effective doses from alpha particles, as compared with beta particles or gamma rays, result from their relatively high energies combined with their very short ranges in tissue. Alpha particles are notable among environmental carcinogens because of their potent ability to produce a high proportion of double-strand DNA breaks per particle. Double-strand DNA breaks are more difficult for the body to repair.

Compared with alpha particles, beta particles are light and fast electrons with a mass of about 1/2000th of a proton. Beta particles have greater penetrating power than alpha particles, but have much less ability than alpha particles to ionize tissues and cause disruptions of the DNA. Beta particles present both an external and an internal radiation hazard. Beta particles can travel over 50 cm in air and, if an individual is externally exposed, beta particles can penetrate the dead layer of the skin and reach the germinal layer of the skin. In most exposure scenarios related to uranium mining and processing, beta radiation presents a greater external than internal radiation hazard. For example, the beta dose rate from uranium decay products is negligible immediately after separation of uranium, but can produce a beta dose rate on contact of about 150 mrem/hr several months after separation because of the buildup of ^{234}Th (USNRC, 2002).

Gamma rays are not particles, but rather are highly penetrating electromagnetic radiation traveling at the speed of light. Gamma rays do not have a charge or mass; they are highly penetrating radiation that can ionize atoms in the body directly or cause "secondary ionizations" when their energy is transferred to atomic particles such as electrons. In most exposure scenarios related to uranium mining and processing, gamma rays present a greater external than internal radiation hazard.

The energy deposited by alpha, beta, or gamma radiation can damage or kill cells. The impact of radiation on a cell depends on the duration of radiation

exposure, the dose rate of the exposure, the total amount of energy absorbed, and the tissue or organ exposed. If radiation damages a cell's genetic material (DNA) and the cell survives, this damage can initiate cancer. The risk of cell damage increases with increasing dose. Although radiation-induced heritable mutations have not been documented in the children of uranium mine or processing workers, or in the children of Japanese atomic bomb survivors, there is some very limited evidence (lacking consistent findings of exposure-response) suggesting that radiation-induced heritable mutations may occur in humans (NRC, 2006; Kodaira et al., 2010; Bunin et al., 2011; Tawn et al., 2011).

The radionuclides of greatest health-related concern in uranium mining and processing are those present in the uranium-238 (^{238}U) (Figure 5.1), uranium-235 (^{235}U) (Figure 5.2), and thorium-232 (^{232}Th) decay series. The potential for occupational exposure to uranium or thorium and their decay products can vary greatly depending on numerous factors, including the type of ore deposit, uranium grade, mineralogy of deposit, production capacity, uranium mining method, production rate, variation in process methods (e.g., types of crushers or grinders), reagents used in the chemical dissolution of uranium-bearing mineral species, solid-liquid separation method, purification method, precipitation, packaging, transportation, waste treatment (e.g., effluent treatment, or water treatment), storage of tailings, environmental conditions around the plant (e.g., hydrological balance and local geology), and engineering controls and safeguards. Although ^{232}Th sometimes occurs in high concentrations in uranium deposits, limited data suggest that presently known commercially viable uranium occurrences in Virginia (see Chapter 3) are unlikely to contain high ^{232}Th concentrations.

In addition to ^{238}U, the radionuclides of greatest health concern in this decay series are uranium-234 (^{234}U) with a 240,000-year half-life, thorium-230 (^{230}Th) with its 77,000-year half-life, radium-226 (^{226}Ra) with a 1,600-year half-life, and the short-lived radon-222 (^{222}Rn) decay products—polonium-218 (^{218}Po), polonium-214 (^{214}Po), and polonium-210 (^{210}Po). In modern uranium processing facilities, over 97 percent of the uranium in the ore can be extracted. However, other radionuclides with potential adverse health effects, including ^{230}Th, ^{226}Ra, ^{222}Rn, and ^{210}Po, and their decay products, remain in the tailings and other waste materials generated by the extraction. In fact, about 85 percent of the original radioactivity in the ore remains after the uranium is extracted. Of particular note, the 77,000-year radioactive half-life of ^{230}Th provides a constant source of ^{226}Ra. Both radionuclides (^{230}Th and ^{226}Ra) are common components of leached materials and airborne dusts from uranium ore tailings and waste piles, and ^{230}Th and ^{226}Ra can pose a health hazard if inhaled or ingested. Radium-226 and its decay products present both an alpha (e.g., internal exposure hazard) and a gamma (e.g., external exposure hazard from the decay products bismuth-214 and lead-214) radiation hazard to miners as well as to uranium processors.

A summary of the major radon and uranium series occupational exposure standards is presented in Table 5.1; note that this table is not intended to be an

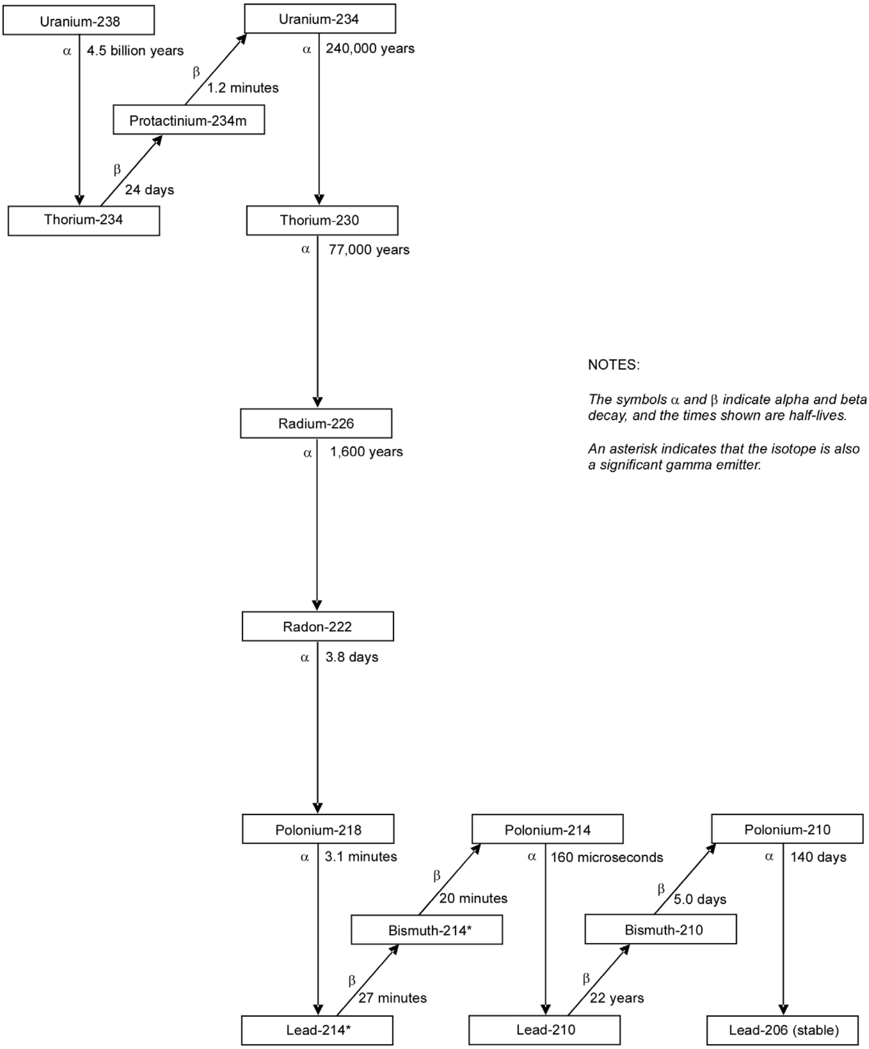

FIGURE 5.1 Uranium-238 decay series. SOURCE: Modified from Argonne National Laboratory, Environmental Science Division (available at http://www.ead.anl.gov/pub/doc/natural-decay-series.pdf).

exhaustive compilation of all recommendations regarding radon and uranium occupational exposure limits, but rather is intended to highlight the complexity and the differences among the guidelines as context for ensuing descriptions of dose and exposure standards and regulations both in this chapter and in Chapter 7. For additional background, Box 5.1 presents a summary of the rather confusing

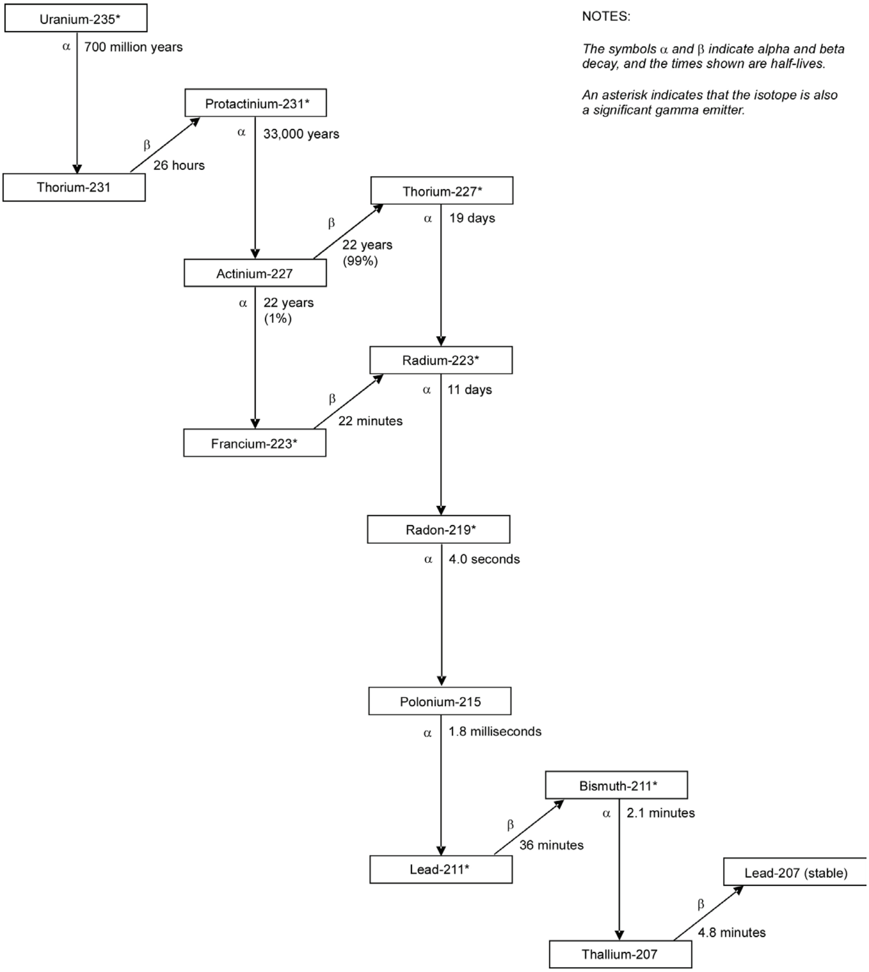

FIGURE 5.2 Uranium-235 decay series. SOURCE: Argonne National Laboratory, Environmental Science Division (available at http://www.ead.anl.gov/pub/doc/natural-decay-series.pdf).

terms and units used for radiation activity, exposure, and dose. Additional information on current regulations and guidelines applicable to uranium is available in ATSDR (2011).

The type of radiation exposure that may be encountered in uranium mining and processing varies by source material and work process (Table 5.3). For example, uranium miners working in underground mines generally have a much greater potential for exposure to radon and radon decay products during the min-

ing process as compared with miners working in open-pit mines (UNSCEAR, 2000). In addition to radon and its short-lived alpha-emitting decay products (i.e., ^{218}Po, ^{214}Po), other important sources of airborne radioactivity in the mine include the longer-lived radioactive decay products of ^{238}U and ^{235}U (e.g., ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Po) (Ahmed, 1981). Work with processed uranium (e.g., yellowcake) generally only increases the potential for alpha exposure. However, drums containing yellowcake that have been stored for several months can lead to increased exposure to x-rays as a result of the interaction of beta particles from aged yellowcake with the steel drums; the beta surface dose is about 150 mrem/hr after a few months (USNRC, 2002) (this potential beta and x-ray exposure is not included in Table 5.3). Work with materials that have undergone uranium separation (e.g., mine or processing plant tailings) primarily presents an alpha and gamma radiation hazard. Process workers in proximity to materials that are being tipped into comminution equipment (grinder) are often at greater risk from airborne exposure to radioactive materials, while those performing maintenance on such equipment may be at higher risk of gamma radiation exposure.

Worker radiation exposures most often occur from inhaling or ingesting radioactive materials or through external radiation exposure. Generally, the highest potential radiation-related health risk for uranium mining or processing facility workers is lung cancer associated with inhaling uranium decay products (more specifically, radon decay products), as well as other non-lung-cancer risks associated with gamma radiation exposure on-site. Nonoccupational radiation exposures to the general population can occur from airborne dispersal of radioactive particulates to off-site locations, including subsequent resuspension, or gases from mining operations, processing facility exhausts, waste rock, wastewater impoundments, or tailings. Exposures may also occur by release of contaminated water or leaching of radioactive materials into surface or groundwater sources where they may eventually end up in potable water supplies. Radon and its decay products can also be transported off-site, especially from tailings or waste areas, in the form of radon gas or radon decay products. The potential for internal radiation exposure from drinking water contaminated with radionuclides (e.g., ^{226}Ra, ^{228}Ra, ^{230}Th, uranium) that have been leached or otherwise released from tailings or other wastes is a common health concern for the public (Landa and Gray, 1995; Baker, 2010). Another health concern for people living near mines and processing facilities is the potential for off-site radiation exposure from atmospheric deposition of "fugitive" ore or tailings dust (e.g., dust containing uranium, ^{226}Ra, ^{230}Th, ^{210}Pb, ^{210}Po, and other radionuclides). Even though such fugitive dusts are extensively diluted once they leave the plant or mine boundaries (Thomas, 2000), accumulation in the food chain can occur with subsequent human consumption of wild or domestic animal meat, fish, or milk.

Additional information concerning a selection of the major radionuclides of health interest (^{222}Rn, ^{238}U, ^{226}Ra) is presented below.

TABLE 5.1 Selected Radon and Uranium Decay Series Occupational Exposure Regulations and Standards

Agency	Regulation/ Recommendation	Applicable Facilities/ Activities	Recommended Radon Exposure Level/Limit
NIOSH	Publication No. 88-101	Underground mines	REL = 1 WLM/yr @100% progeny equilibrium = 8.3 pCi/L
IAEA	Basic Safety Standard 115 (1996) and Safety Report Series No. 33	All workplaces other than mines (includes exposure to naturally occurring radon not related to production activities)	Intervention level: 1,000 Bq/m^3 (27 pCi/L) Assumes 2,000 hours exposure per year and 0.4 equilibrium factor
IAEA	Safety Guide No. RS-G-1.6	Activities involved in the mining and processing of raw materials	14 mJ·h·m^{-3} (20 mSv) 35 mJ·h·m^{-3} (50 mSv)
MSHA	30 CFR Part 57	Underground mines	4 WLM/yr Max = 1 WL
USNRC	10 CFR Part 20	Uranium processing facilities and in situ leaching facilities	DAC @100% equilibrium: 30 pCi/L ALI = 4 WLM
OSHA	29 CFR § 1910.1090	Processing facilities not regulated by the U.S. Atomic Energy Act[a]	DAC@100% equilibrium: 30 pCi/L ALI = 4 WLM[b]
DOE	10 CFR Part 835	DOE facilities	DAC @100% equilibrium: 80 pCi/L ALI= 10 WLM
ICRP	Publication 103: The 2007 Recommendations of the International Commission on Radiological Protection	Workplaces	Action Level (Bq/m^3): 1000 Occupational Limit: 4 WLM/yr averaged over 5 years; 10 WLM in a single year

[a]Note that this is an extremely complicated area of policy, law, and regulation; see discussion in Chapter 7 of the division of responsibilities between the U.S. Nuclear Regulatory Commission (USNRC), the Mine Safety and Health Administration, and the Occupational Safety and Health Administration (OSHA).

[b]When OSHA issued its ionizing radiation regulations in 1971, they referenced the 10 CFR Part 20 limits that were currently in existence. When the USNRC revised the 10 CFR Part 20 limits in 1991, this created some uncertainty as to which limits would apply.

U and Progeny Particulate Limit	External Exposure Limit	Total Exposure Limit	Workplace Controls
Not addressed	Not addressed	Not addressed	Continuous ventilation required to reduce radon to 1/12 WL Respirators to be used if the average concentration cannot be reduced to 1/12 WL
Not addressed	Not addressed	Effective dose of 20 mSv/year averaged over 5 years, not to exceed 50 mSV in 1 year	Potential remediation measures discussed
ALI for U Ore dust = 5,700 Bq (20 mSv) and 14,000 Bq (50 mSv)	Limits are governed by the total exposure from internal and external	Effective dose of 20 mSv/year averaged over 5 years, not to exceed 50 mSV in 1 year	Respirators recommended only for short-duration tasks
None stated	5 rem/yr	Not addressed	Respiratory protection required at levels ≥10 WL
Limits specified in Table 1 of Appendix B of 10 CFR Part 20	Limits are governed by the total exposure from internal plus external	Total Effective Dose Equivalent of 5 rem	
References USNRC limits specified above	1.25 rem per quarter		Posting required at 25% of the exposure limit
Limits specified in Appendix A of 10 CFR Part 835	Limits are governed by the total exposure from internal and external	Total Effective Dose Equivalent of 5 rem	Posting required at 10% of the DAC
Not addressed	Not addressed	Effective dose of 20 mSv/year averaged over 5 years, not to exceed 50 mSV in one year	Not addressed

NOTES: WLM = working level month, DAC = derived air concentration, ALI = annual limit on intake, REL = recommended exposure limit.
SOURCE: Courtesy Jim Neton, NIOSH, with modifications.

BOX 5.1
Common Units and Terms Used for Radiation Activity, Exposure, and Dose

The activity, or rate of nuclear transformations, of a radionuclide is expressed in disintegrations (or decays) per unit of time. The two units for radiation activity are the curie (Ci) and the S.I. unit becquerel (Bq).

1 Bq = 1 disintegration/second
1 Ci = 3.7×10^{10} disintegrations/second
1 Ci = 3.7×10^{10} Bq

Radiation dose is expressed in units of absorbed dose or dose equivalent. Absorbed dose refers to the total ionizing radiation absorbed by a unit mass of substance, while the dose equivalent refers to an absorbed dose weighted for the type of radiation being measured (called the quality factor, see table below). The dose equivalent is used in addition to the absorbed dose because different types of ionizing radiation have the capacity to do different amounts of damage to biological tissue. The units for absorbed dose are the rad and the S.I. unit Gray (Gy). The units for equivalent dose are the rem and the S.I. unit sievert (Sv).

1 Gy = an absorbed dose of 1 Joule of ionizing radiation/kilogram of matter
1 rad = 0.01 Gy
1 Sv = an absorbed dose × quality factor Q (see Table 5.2)
1 rem = 0.01 Sv

Cumulative radon decay product exposure is often measured in working levels (WL) and working level months (WLM). The working level is any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha particle energy. A working-level month is an exposure to 1 working level for 170 hours (2,000 working hours per year/12 months per year).

The equilibrium factor is the ratio of decay products to radon.

SOURCES: USNRC, IAEA Basic Safety Standard.

RADON HEALTH HAZARDS

Three radon isotopes are generated in the ^{238}U, ^{235}U, and ^{232}Th decay chains, including radon-222 (radon), radon-219 (actinon), and radon-220 (thoron). These are the immediate decay products of ^{226}Ra, radium-223 (^{223}Ra), and radium 224 (^{224}Ra), respectively. Because ^{235}U has low abundance in natural crustal rock, as compared with ^{238}U, and because of the relatively short radioactive half-life of its radon decay product, actinon (Figure 5.2), ^{235}U is generally not considered to be a significant health risk as compared with ^{238}U in the mining and processing

TABLE 5.2 Quality Factors and Absorbed Dose Equivalencies

Type of Radiation	Quality Factor (Q)	Absorbed Dose Equal to a Unit Dose Equivalent
X, gamma, or beta radiation	1	1
Alpha particles, multiple-charged particles, fission fragments, and heavy particles of unknown charge	20	0.05
Neutrons of unknown energy	10	0.1
High-energy protons	10	0.1

SOURCE: http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1004.html#N_1_201004; accessed November, 2011.

TABLE 5.3 Simplified Matrix Showing Potential Exposure Types and Some of the Major Radionuclides Associated with Different Mining and Milling Processes That Have the Potential to Cause Adverse Health Effects (X indicates elevated potential for exposure)

Process	Radiation Type	Uranium	Radium-226	Radon-222
Mining				
Underground mining	α γ			X
Surface mining	α γ			X
Processing				
Ore receiving/crushing	α β γ	X	X	X
Grinding Wet slurry	α β γ	X	X	X
Chemical dissolution/leaching	α β γ	X	X	X
Solid-liquid Separation	α β γ	X	X	X
Solid Liquid Separation—Liquid phase	α	X		X
Extraction (SX or IX)	α	X		X
Purification, Elution/stripping	α	X		
Precipitation	α	X		
Drying/packaging	α	X		
Transportation	α			
Tailings	α β γ		X	X
Postclosure	α			X
Off-site	α		X	X

setting. In addition, the majority of uranium deposits in Virginia are thought to contain low concentrations of ^{232}Th (see Chapter 3). Therefore, thoron, a radioactive decay product of ^{232}Th, as noted above, is anticipated to present a much lower risk to workers than exposure to radon-222 decay products.

Radon-222, hereafter referred to as radon, is a colorless and odorless gas that possesses no sensory reminders that provide an alert to its presence. It is ubiquitous in soils, rocks, and groundwater supplies. Radon has the longest half-

life among the 35 known isotopes of radon, including the other two forms (i.e., actinon and thoron) noted above. Because of the relative abundance of radon, its relatively long half-life compared with the other radon isotopes, as well as its alpha-emitting decay products, protracted exposure even at background levels accounts for an adverse human health risk, while exposure exceeding such background levels contributes a further increased incremental adverse health risk.

Radon is formed from the radioactive decay of radium-226 (Figure 5.2). It has a half-life of 3.8 days and decays into a series of radioactive solid decay products, ending with stable lead-206. The radon decay products, particularly ^{218}Po and ^{214}Po, deliver the primary radiation dose to the respiratory epithelium, rather than the radon gas itself. After the decay of radon gas, the short-lived solid decay products that remain suspended in air undergo varying degrees of attachment to ambient aerosols. The percentage of decay products that attach is influenced by numerous factors, including air movement and aerosol concentration as well as ambient particle size. Pulmonary deposition of radon decay products depends on particle size (which is affected by the proportion of attached or unattached decay products), volume of air displaced between normal inspiration and expiration, breathing rate (which is affected by mining or processing-related physical activity), nasal versus oral breathing (which is also affected by mining- or processing-related physical activity), and lung volume. The quantity and distribution of deposited radon decay products is influenced by mechanisms that remove the radon decay products from the lung or move them to other areas of the lung and body (NRC, 1991, 1999b; ATSDR, 2008).

Once deposited in the lung, the short-lived radon decay products, ^{218}Po and ^{214}Po, rather than the radon gas, deliver the majority of the radiation dose in the form of alpha particles to the respiratory epithelium. Alpha particles impart a high density of ionizations along their short path (i.e., high linear energy transfer), a process that results in DNA damage. Radiation-induced carcinogenesis is thought to arise from DNA damage to a single cell (i.e., cancer is monoclonal in nature). NRC (1999b) concluded not only that there is overwhelming evidence supporting such a monoclonal cancer origin, but also that there is no apparent threshold for radon-induced lung cancer. Radon-caused lung cancer is one of the earliest recognized forms of occupational cancer. An overview of the earlier history of radon-caused cancer of the lung is presented in Box 5.2.

Mining-Based Epidemiological Studies of Radon Health Effects

The highest radon-related exposures to workers generally occur during underground uranium mining operations. However, significant radon exposure can also occur in open-pit mines, for example, as a result of meteorological factors such as air inversions. As noted above (Table 5.3), radon exposures can also occur during several of the steps in uranium ore processing as well as from radon emanation from tailings and from mining and processing wastes. Findings

from early studies of radon-exposed underground miners performed in Central Europe (see Box 5.2), as well as more formal epidemiological investigations of underground miners in the United States (e.g., Wagoner et al., 1965), provided very strong evidence by the mid-1960s to causally link protracted radon decay product exposure with lung cancer (UNSCEAR, 2009; Samet, 2011).

Over 20 retrospective epidemiological studies examining the association between radon and cancer mortality have been performed in North America, Europe, and China. In a typical retrospective radon-related cohort mortality study, the investigators identify a cohort of exposed workers (e.g., underground radon-exposed uranium or hard-rock miners) and then determine their disease experience (i.e., cancer occurrence) many years after their initial mining exposures. The assessment of retrospective radon exposure, as well as other important exposures in the same workplace (e.g., diesel, arsenic, and silica co-exposures), presents a key challenge when conducting such studies. In most cases, the retrospective assessment of radon decay product exposure has been based on periodic area measurements (e.g., a particular tunnel) of radon decay products rather than on measurements of radon decay product concentrations in close proximity to where the miners worked as would be done if personal dosimetry data for radon exposure were available. The collection of important lifestyle information, such as cigarette smoking, has also been lacking in many of the retrospective cohort mortality studies of underground radon-exposed miners. Even with these limitations, the overwhelming majority of the epidemiological studies have demonstrated a positive linear dose-response relationship between radon decay product exposure and lung cancer; that is, the greater the exposure, the greater the risk, falling on a straight line (Samet, 1988; NRC, 1999b; ATSDR, 2008).

To develop a more comprehensive assessment of the risk posed by protracted radon exposure that included adjustment for potential concomitant risk factors for lung cancer (e.g., smoking, silica exposure), data have been pooled (i.e., combined) from multiple retrospective mortality studies to increase the sample size available for analyses (NRC, 1988). A pooled epidemiological study is a type of combined study that collects the raw data from the studies and uses these data for a new overall analysis. The most extensive pooling of data from retrospective cohort mortality studies of radon was performed by Lubin and colleagues (1994) and served as the basis for a subsequent pooling by the NRC's Committee on the Biological Effects of Ionizing Radiation (BEIR VI; NRC, 1999b). The BEIR VI analysis pooled data from 11 radon-exposed retrospective mortality studies of miners with very long follow-up of mortality and included nearly 2,800 lung cancer deaths. The pooled cohort data included radon-exposed miners from the United States, Canada, Australia, France, the Czech Republic (at that time part of Czechoslovakia), Sweden, and China. Each of the 11 studies had independently found increased lung cancer mortality rates associated with increased exposure to radon and its decay products (Lubin, 2010). For comparison, the mean cumulative radon exposure from the pooled miner studies is

BOX 5.2
Early History of Lung Cancer and Uranium Miners

Although it is broadly appreciated by the general public that radioactive exposures—including radon—carry adverse effects, this has not always been the case. In particular, the link between occupational exposure to radon and lung cancer has been poorly appreciated, with delayed governmental actions despite more than two centuries of mining-related mortality attributable to this cause (Figure 5.3). The following is a brief overview of that history, emphasizing the public health aspects of occupation-related lung cancer among radon-exposed miners.

Although Paracelsus (Sigerist, 1941) and Agricola (1556 [1950]) had earlier addressed miner's lung disease, the first description of morbidity likely to be due to radon gas appeared in 1770, when Carl Lebrecht Schefflers published a seminal work on the health of miners, *Abhandlung von der Gesundheit der Bergleute* (Schefflers, 1770). Although broad in scope, it gives particular emphasis to the health of the cobalt miners of Schneeberg and nearby Annaberg, where cobalt had become a sought-after metal for alloying purposes. Because uranium-bearing ores were mineralogically linked to the cobalt, this meant that mining cobalt increased exposure to radon. Some of Scheffler's key observations included the very early mortality of those exposed, with a rapid downhill course once disease was first manifest; the attribution of disease to an inhaled gas or emanation, rather than dust per se; and the higher prevalence of illness in a particular cobalt mine in Schneeberg characterized by very long and poorly ventilated galleries that the miners had to transverse to reach the rock face.

It was still another century before landmark medical reports appeared firmly establishing the link between employment in the mines of Schneeberg and neoplasm of the lung. An initial 1878 notice of the phenomenon by an area public health officer was followed a year later by an extensive report he coauthored with a local mine doctor in Schneeberg (Hesse, 1878; Härting and Hesse, 1879). This latter publication meticulously details the occurrence and clinical histories of lung cancer cases of Schneeberg miners. The eponymously named *Schneeberger krankheit* was reported to account for 150 deaths among a cohort of 650 miners (23 percent mortality) over the 10-year period from 1869 to 1877, at a time when lung cancer was a rare entity.

Over the ensuing 50 years, accumulating medical reports further documented the extent of the *Schneeberger krankheit* among these mine workers, although confusion remained over the pathological specifics and, more importantly, lack of certainty as to the nature of the cancer-causing agent (arsenic was initially suspected) (Schüttmann, 1993). There was, however, no substantive intervention to decrease the work-related mortality of mines, estimated by the 1920s to have reached a > 50 percent lung cancer death rate among the radium-mining workforce, so blatant an effect that the *Schneeberger krankheit* was recognized as an occupational disease and compensated as such by the German authorities (Proctor, 1999).

Throughout this early period, lung cancer in miners was of little public health concern in the United States, despite an emerging medical interest in occupational

continued

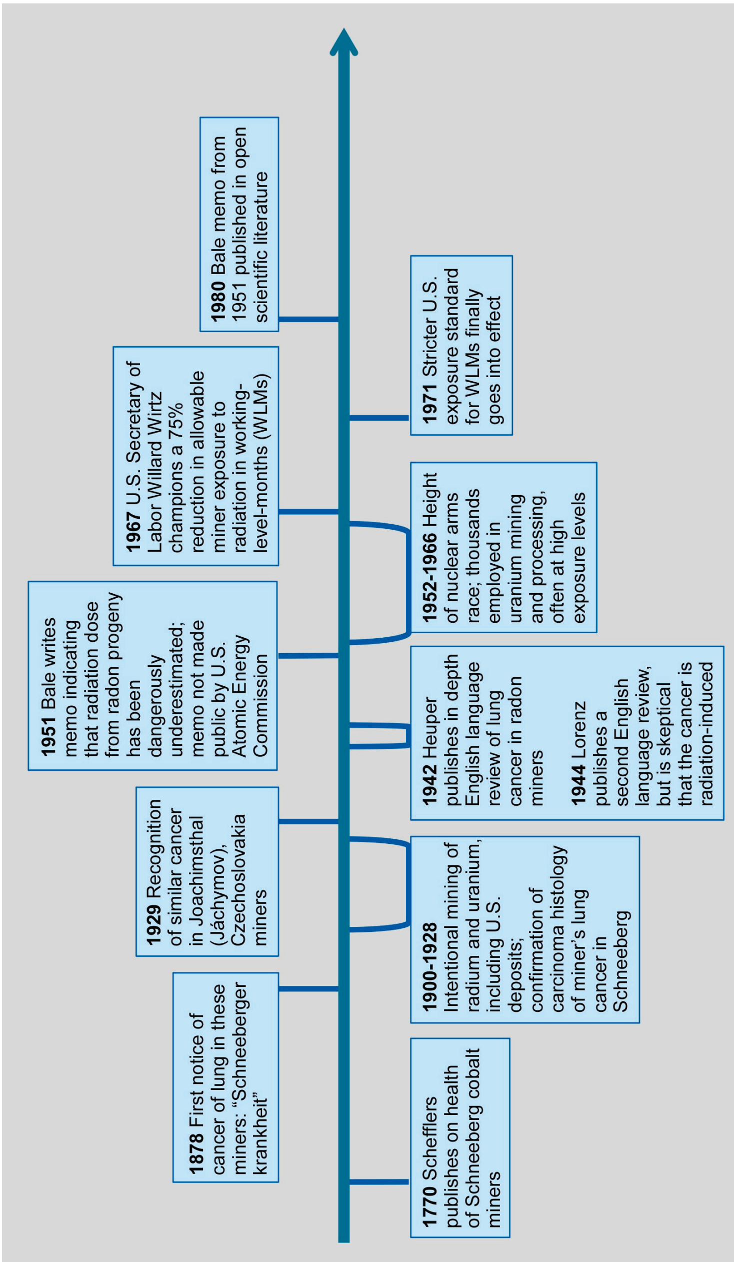

FIGURE 5.3 Historical time line for the understanding of lung cancer occurrences in uranium miners. SOURCE: Courtesy of P.D. Blanc.

BOX 5.2 Continued

diseases such as lead poisoning and silicosis, both of which were tied to mining or metal working. This does not mean that radium and uranium mining itself went ignored in the United States—a U.S. Bureau of Mines publication, *A Preliminary Report on Uranium, Radium, and Vanadium,* was first published in 1913 and appeared in two more editions through 1916 (Moore and Kithil, 1916). This monograph underscores the U.S. government's role in promoting the already rapidly growing domestic exploitation of these materials, emphasizing radium as a new and nearly miraculous treatment that should not be exported abroad, explicitly stating, "The uranium deposits of Colorado and Utah are being depleted rapidly by foreign exploitation and it would seem almost a patriotic duty to develop an industry to retain the radium in America" (Moore and Kithil, 1916, p. 7). The report carries no mention of health risks.

Until well into the 20th century, the bulk of the biomedical literature on lung cancer in miners of cobalt and later radium and uranium ores was published solely in European German-language journals. This status changed dramatically, however, with the appearance in 1932 of a paper in English from Czech investigators detailing the etiology and extent of lung cancer among Joachimsthal miners (Prichan and Šikl, 1932). This publication was followed by a 1942 text, *Occupational Tumors and Allied Diseases* (Hueper, 1942), which dealt not only with miners but also with others working with radioactive substances. Hueper was unequivocal in his conclusions, noting that although all attempts had failed to demonstrate experimentally a consistent carcinogenic action of radioactive substances upon the pulmonary tissue, the evidence of statistical epidemiological and clinical observations left little doubt that these agents represented the chief cause of the pulmonary malignancies observed in workers exposed to radioactive matter due to occupation (Hueper, 1942). Hueper's cogent assessment, however,

approximately 10 times higher than the exposure an individual would receive from spending a protracted period (e.g., decades) in a home with radon concentrations similar to the U.S. Environmental Protection Agency's (USEPA) Radon Action Level of 4 pCi/L.

Every study of miners examined in the BEIR VI report (NRC, 1999b) included the range of exposures that overlap with the cumulative exposures experienced in homes at the USEPA's Radon Action Level of 4 pCi/L (Lubin, 2010). The BEIR VI estimates of the risks posed by lower level radon decay product exposures are particularly relevant to the general public living near uranium mining and processing operations, because radon decay product exposure has been shown to be an important source of radiation exposure to nearby offsite communities (SC&A, 2011).

Numerous factors affected the excess relative risk related to radon decay product exposure quantified in working level months (WLM). A WLM is used

was dismissed by a 1944 review appearing under the aegis of the National Cancer Institute (NCI). This review emphasized the lack of an animal model supporting radon-associated lung cancer risk, and even suggested that eugenic self-selection among multigenerational uranium miners might explain the phenomenon (Lorenz, 1944). In addition to a prominent role at the NCI, this author was also closely associated with the Manhattan Project (Kaplan, 1955).

In 1951, a new analysis finally explained the biological potency of radon progeny alpha exposure, but unfortunately this crucial analysis remained an internal governmental document and did not appear in the open peer-reviewed biomedical press until nearly three decades later (Bale, 1980). The central findings of this analysis, however, were included in a 1955 report by Duncan Holaday, a key U.S. Public Health Service scientist who, footnoting Bale as an unpublished source, reported that the radon-related radiation dose delivered to U.S. miners was likely to be 100 times higher than that previously calculated (Holaday, 1955). Holaday pressed those responsible for the federal health and safety oversight to take additional protective actions, but met with considerable resistance (Udall, 1998). Over time, the United States had its own ample epidemiological confirmation that uranium was a potent risk factor for lung cancer among those occupationally exposed in Colorado and New Mexico. By 1967, these epidemiological observations were being noted in the popular news media (Reistrup, 1967), and the then-Secretary of the U.S. Department of Labor began to champion a far lower occupational exposure limit for radon in working level months (WLMs)—industry argued for 36 WMLs, various governmental representatives pushed for 12 WMLs, but the Department of Labor overruled these positions and promulgated a 3.6 WML level (i.e., an order of magnitude less than the industry target) (MacLaury, 1998). The new standard, rounded-up to 4 WLMs, did not go into effect until 1971 (Morgan and Samet, 1986).

to quantify cumulative exposure to radon decay products (see glossary for more details[1]). The risk estimate was affected by smoking history, dose rate, and age at exposure. For example, the BEIR VI committee observed that exposure to both radon and tobacco usage increases lung cancer risk higher than simply an additive effect, but less than a full multiplicative degree of risk. Thus, the risk of lung cancer among uranium miners who smoke cigarettes is greater, in absolute and relative terms, than the risk for cigarette smokers who do not experience radiation exposure; moreover, the incremental increase in absolute risk (reflected in

[1] Radon decay product concentrations are expressed in working levels (WL). A WL is equal to the total alpha energy released from the short-lived radon decay products in equilibrium with 100 pCi of radon gas per liter of air. Thus, if a worker is exposed to 0.166 WL for 1 month (170 hours), that worker's cumulative exposure for that month would be 0.166 working level months (WLM). Exposure at the end of 12 months at a monthly exposure of 0.166WLM would yield a cumulative exposure of 2 WLMs.

the rate of lung cancer among those concomitantly exposed) is more than simply the rates added together—thereby indicating a degree of synergism—even though the combined rate may not be as high as the cross-product of the rates multiplied against each other. The International Council of Radiation Protection (ICRP, 2012) indicates, based on the pooled results from radon-exposed miner studies, that a lifetime excess absolute risk of 5×10^{-4} per WLM should be used as the nominal probability coefficient for radon progeny-induced lung cancer.

Since the publication of the BEIR VI Report, additional findings from other radon-related miner studies further support the findings of the BEIR VI report (e.g., Villeneuve et al., 2007; Schubauer-Berigan et al., 2009; Kreuzer et al., 2010; Lane et al., 2010; Leuraud et al., 2011). Additional information summarizing the experience of radon-exposed miner cohorts is presented in the report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2009).

Although the occupational lung carcinogenicity of radon decay product exposure has been clearly established for decades, the causal association between occupational radon exposure and cancer of other types (i.e., nonlung cancer), as well as radon-related non-cancer adverse health outcomes, has been less clear. Such endpoints are of concern because, in addition to the respiratory epithelium, protracted radon decay product exposure can deliver varying degrees of radiation dose to other sites in the body, including the skin, bone marrow, and kidney (Kendall and Smith, 2002). Several researchers have published findings that are suggestive of an association between occupational radon decay product exposure via mining and leukemia, as well as cancers of the stomach, liver, and trachea (Darby et al., 1995; Kreuzer et al., 2008, 2010).

Since retrospective mortality studies generally rely on adverse health outcomes noted on death certificates or mortality registries, cancers with a long survival period—or other non-cancer adverse health conditions that cannot be accurately determined—cannot be assessed with the same reliability as for lung cancer, from which survival is generally not extended. For example, Bedford (2010) found that the ability of death certificates to document cancer occurrence is directly related to the survival period of the cancer. Cancers with relatively short survival periods (e.g., pancreatic cancer, lung cancer) are more likely to be noted on a death certificate. One of the few studies to examine cancer incidence, rather than mortality, was performed by Řeřicha et al. (2006) in Czech uranium miners and reported a positive association between radon exposure and leukemia, including chronic lymphocytic leukemia. Additional well-designed epidemiological studies are required to assess further the possible association between radon decay product exposure and other adverse health outcomes (Linet et al., 2007; Field, 2010). The need for additional epidemiological studies is particularly crucial for radon-exposed female workers, because there is little information on radon decay product exposure and the occurrence of female-specific cancers, for example, cancer of the breast or ovaries (Field, 2010).

Studies examining possible associations between protracted radon exposure and non-cancer adverse health outcomes are almost nonexistent (NRC, 1999b). Archer and colleagues (1976) noted a linear positive relationship between radon decay product exposure and nonmalignant respiratory disease in nonsmoking uranium miners, that the authors attributed to diffuse parenchymal radiation damage.

Occupational Exposure Guidelines for Radon

In many cases, the primary radiation risks associated with uranium mines and processing facilities are exposure to radon decay product exposure (Ahmed, 1981; NIOSH, 1987) and gamma radiation. Although the radon decay product concentrations measured in mines today are expected to be less than those that were routinely observed in the past, there have been efforts by NIOSH to lower (i.e., make more protective) the allowed exposure promulgated in the current U.S. standards (NIOSH, 1987). The current Mine Safety and Health Administration (MSHA) and Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for cumulative radon decay product exposure is 4 WLM per year[2] (Table 5.1). Using the ICRP risk estimate of 5×10^{-4} lifetime risk of lung cancer per WLM as cited above, the 4 WLM/yr limit at 30 years of exposure would result in a 6 percent increase in lifetime risk of lung cancer (i.e., 600 per 10,000 persons thus exposed). The quantitative risk assessment performed by the U.S. National Institute for Occupational Safety and Health (NIOSH) in the 1980s concluded that exposures to 1 WLM per year over a 30-year working lifetime posed substantial health risks (NIOSH, 1987). Despite such risks, in 1987 NIOSH recommended lowering the PEL from 4 WLM/yr to 1 WLM/yr (NIOSH, 1987). In putting forward the NIOSH recommendation, NIOSH Director and Assistant Surgeon General, Dr. J. Donald Millar noted that although NIOSH was recommending lowering of the PEL to 1 WLM/yr for radon decay product exposure, he did not believe the recommendation satisfied NIOSH's commitment to protect the health of the nation's miners. He went on to state that, "*if new information demonstrates that a lower exposure limit constitutes both prudent public health and a feasible engineering policy, NIOSH will revise its recommended standard*" (NIOSH, 1987, p. vi). Subsequent miner-based studies (Lubin et al., 1994) have provided convincing evidence that a PEL of 1 WLM/yr, even if promulgated, would not provide an acceptable health-based limit to protect worker health.

Environmental Radon Exposure and Health Effects

Radon gas is ubiquitous in both the outdoor and indoor nonoccupational environment. The average indoor and outdoor radon concentration is 1.3 pCi/L and 0.4 pCi/L, respectively, in the United States (USEPA, 1992). Both indoor

[2]See 30 CFR §§ 57.5047, 57.5038.

and outdoor radon environmental concentrations often undergo significant temporal and spatial variation (Fisher et al., 1998; Steck et al., 1999; Zhang et al., 2007). In some areas of the United States, the average year-long outdoor radon concentration can equal that of the national indoor average radon concentration (i.e., 1.3 pCi/L) (Steck et al., 1999). The USEPA has assigned each county in the United States to one of three radon potential zones based on numerous factors, including short-term indoor radon measurements, aerial measurements of uranium, geology, soil permeability, and building foundation type. Zone 1 counties have a predicted average indoor screening (i.e., short-term test generally performed in the basement) radon measurement greater than 4 pCi/L. Zone 2 counties have predicted indoor average screening measurements ≥ 2 and ≤ 4 pCi/L. Zone 3 counties have a predicted average radon screening measurement of < 2 pCi/L. In the early 1980s, the National Council on Radiation Protection (NCRP) estimated that the average effective dose of radiation per individual in the United States was 3.6 mSv; by 2006, the average dose had increased to 6.2 mSv, primarily as a result of medically related procedures (NCRP, 2009). Radon decay product exposure delivers 37 percent of the total effective dose per individual in the United States (Figure 5.4) (NCRP, 2009).

The radon exposure potential within the boundaries of the Commonwealth of Virginia is highest in the eastern Piedmont along the Fall Line, the western Piedmont, and the Valley and Ridge province (USEPA, 1993a; VA DMME, 2006) (Figure 5.5). In a 1991-1992 statewide survey of 1,156 homes performed by the USEPA and the Virginia Department of Health, the average radon concentration was 2.7 pCi/L, with 17.6 percent of homes exhibiting screening radon concentrations above 4 pCi/L. The maximum residential radon screening measurement recorded was 81.5 pCi/L, in a home in Danville, Pittsylvania County, Virginia (USEPA, 1993a). The Virginia Department of Mines, Minerals and Energy (VA DMME) indicated that it is, *"reasonable to assume that radon would be a significant problem over the massive uranium deposits in Pittsylvania County"* (VA DMME, 2006). Note that the existing elevated residential radon concentrations in Pittsylvania County, Virginia, are not related to mining activities, but rather are attributable to the strong radium-226 source strength in that geographical area.

Radon Risk Estimates

The NRC's BEIR VI Committee estimated—based on projections (i.e., interpolations from the radon-exposed underground miner studies they examined)—that 18,600 lung cancer deaths occur each year in the United States from nonoccupational exposures to radon decay products (NRC, 1999b). The USEPA updated the risk estimate in 2003, projecting that of the total 157,400 lung cancer deaths that occurred nationally in 1995, 21,100 (13.4 percent) were radon related (USEPA, 2003). The USEPA also estimated that the risks from lifetime exposure

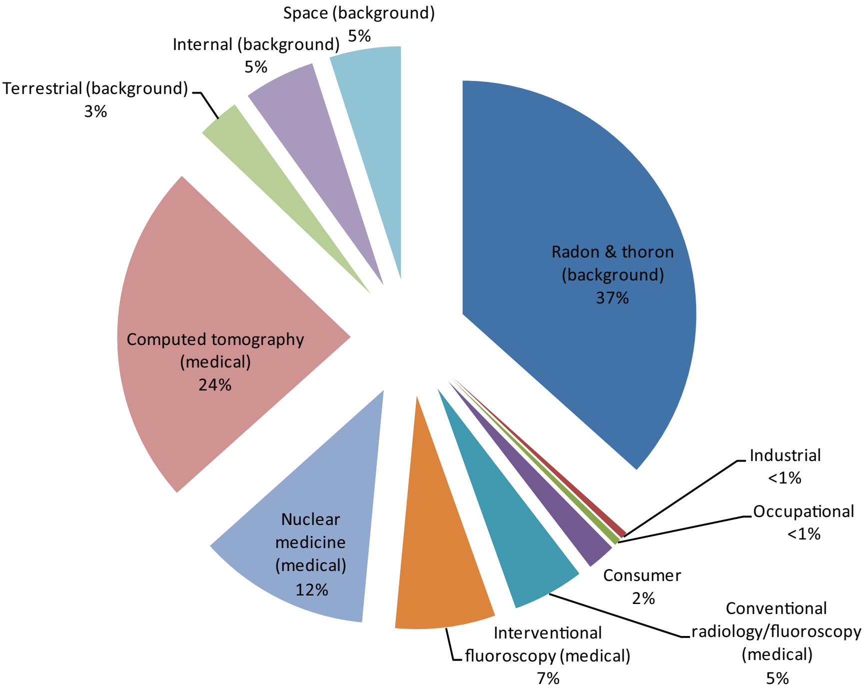

FIGURE 5.4 Percent contribution of various sources of radiation exposure to the total effective dose per individual in the United States for 2006. Percent values have been rounded to the nearest 1 percent, except for those < 1 percent. SOURCE: Reprinted with permission of the National Council on Radiation Protection and Measurements, http://NCRPpublications.org.

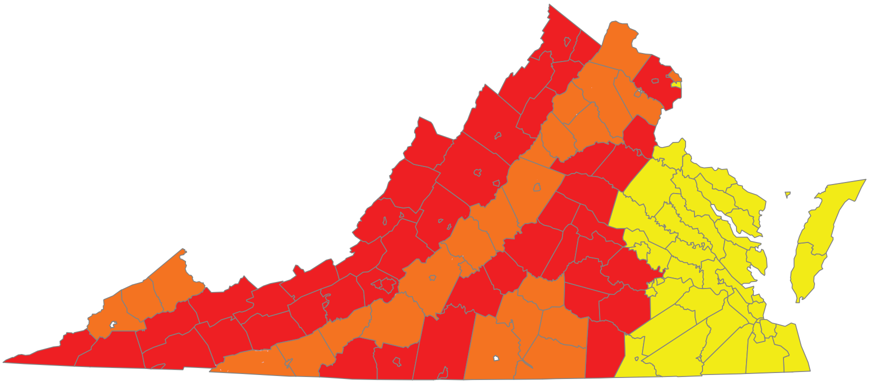

FIGURE 5.5 Radon zones in Virginia; red zones indicate high radon potential, orange zones indicate moderate radon potential, and yellow zones represent low radon potential. SOURCE: VA DMME Division of Geology and Mineral Resources (http://www.dmme.virginia.gov/DMR3/radon.shtml; accessed September 26, 2011.)

at the radon action level of 4 pCi/L are 2.3 percent for the entire population, 4.1 percent for individuals who smoked cigarettes at some time in their lives, and 0.73 percent for individuals who never smoked. The BEIR VI committee and the USEPA note that, although it is not possible to eliminate radon exposure completely, projections from miner-based studies to the residential setting indicate that approximately one-fourth of the radon-related lung cancers could be avoided by lowering radon concentrations in all U.S. homes to no more than the USEPA's radon action level of 4 pCi/L (NRC, 1999b; USEPA, 2003).

As noted above, risk estimates for protracted exposure to radon decay products among the general public are based on the indirect evidence from radon-exposed miners and are subject to multiple uncertainties. For example, the cumulative radon exposure values for miners are often many times higher than those for the general public, the exposure rate is higher for miners than for the general public, the breathing rate and type of breathing (i.e., more oral breathing by miners as opposed to nasal breathing) often differs between miners and the general public, differences in the size of particles to which the radon decay products attach, sex difference (i.e., most miners are men), age differences (i.e., miners generally are over age 18), higher rates of smoking among miners, and the greater exposure to other lung carcinogens among miners. Because of the uncertainties in projecting miner-based risk estimates to nonworker populations, and in order to obtain direct information on the risk posed by residential radon exposure, numerous investigators have performed case-control epidemiological studies that compared the concentration of radon in the homes of cases (i.e., individuals with lung cancer) to the concentration of radon in the residences of age- and sex-matched individuals without lung cancer. Summaries of the findings from 22 major residential case-control studies are available elsewhere (Darby et al., 2005, 2006; Krewski et al., 2005, 2006). Although the risk estimates for protracted radon exposure and lung cancer incidence varied among the studies, 19 of 22 exhibited increased risk estimates at an average long-term radon exposure that was even below (i.e., 2.7 pCi/L) the USEPA's Radon Action Level of 4 pCi/L (Lubin, 2010). Pooling of residential radon studies performed both in North America and Europe (Darby et al., 2005, 2006; Krewski et al., 2005, 2006) yielded quantitative risks estimates that are very comparable to those projected from the radon-exposed miner studies. The pooled epidemiological analyses yielded statistically significant findings for the relationship between protracted radon exposure and lung cancer at concentrations even below the USEPA's Radon Action Level. These findings further support the need to reduce radon exposures for workers involved with uranium mining and processing to as low as reasonably achievable (ALARA).

Consistent with the prevalence of exposure and its adverse effects, residential radon decay product exposure is believed to be the second leading cause of lung cancer overall, the primary cause of lung cancer among individuals who have never smoked, and the leading environmental cause of cancer mortality in

the United States (USEPA, 2009, 2011b; Lubin, 2010; Field, 2011). Moreover, even relatively low-level residential radon concentrations (i.e., less than 2 pCi/L) present a numerically substantial (i.e., on the order of 10,000 excess deaths per year) population-based health risk because of the large population exposed in the United States. To reduce the lung cancer deaths from residential radon exposure by 50 percent, the radon concentration in all the homes in the United States would have to be lowered to ≤ 2 pCi/L (NRC, 1999b; Lubin, 2010). As noted in the USEPA's Physician's Guide for radon (USEPA, 1993b),

> Recognizing that radon is a significant public health risk, scientific and professional organizations such as the American Medical Association, the American Lung Association, and the National Medical Association have developed programs to reduce the health risks of radon. The National Institute for Occupational Safety and Health (NIOSH) reviewed the epidemiological data and recommended that the annual radon progeny exposure limit for the mining industry be lowered (NIOSH 1987).

Radon Releases from Uranium Mining and Processing

While radon is ubiquitous in the Earth's crust, it is generally more concentrated in or near uranium mining and processing operations. Communities living near uranium tailing piles may have increased environmental radon levels (ATSDR, 2008). Sources of radon at uranium mining and processing sites include tailings, uranium ore, waste rock, open cuts or underground mines, the processing facility, and water retention ponds (Mudd, 2008). In many cases, tailings represent the predominant source of radon emission (i.e., off-gassing) from a mining site. Radon emanation is heavily influenced by the specific material's radium activity, moisture content, porosity, and density (Mudd, 2008). The Code of Federal Regulations (10 CFR § 20.1301) restricts the total effective dose (TED) to individual members of the public from licensed processing facility operations to less than 100 mrem per year. Radon and its decay products are specifically excluded from compliance with the dose criteria outlined in the Code of Federal Regulations (40 CFR § 190.10a). However, 40 CFR Part 61, Subpart B limits the effective dose from radon decay products to 10 mrem/yr for members of the public.

On November 10, 2011, a USEPA contractor, S. Cohen & Associates (SC&A), provided the agency with modeled data for radionuclide emissions from processing facility tailings and risk estimates to the population under various scenarios. One of the sample exposure scenario sites selected by SC&A (2011) included a site in Virginia, and SC&A indicated that this site was chosen because of the large number of uranium deposits in Virginia. Specifically, Culpeper County, Virginia, was selected as the Eastern Generic sample study site within Virginia, "because of its high population density and its past experience as a uranium mine lease site."

The location was also selected to exclude members of the general population living within 1 km of the site. The model used in the report included the following input data: an estimate of the 2010 population living within 80 km of the Culpeper County, Virginia site, meteorological data at the site, and an estimate of the amount of radon released on a yearly basis from the site. The maximum estimated radon release rate of 1,750 Ci/yr from the White Mesa, Utah, mine and processing facility tailings site was used as a surrogate measure of the maximum release rate for the Culpeper County site. Based on the estimated release rates and the standard modeling performed by the USEPA contractor, the reasonably maximally exposed individual (RMEI) (i.e., member of the public within 80 km expected to receive the greatest exposure to radon decay products) was estimated to receive a dose of 28 mrem/year, with a 1.6 in 100,000 chance of developing a latent cancer fatality; while the maximum estimated population dose living within 80 km of the site was 200 person-rem/yr, with a 1.4 in 1,000 chance of developing a latent cancer fatality.

The extent to which the estimated radon release rate assumed by SC&A (2011) for the Culpeper County site would approximate potential radon releases from tailings and waste rock in Virginia is not known. Radon emission rates from various types of underground mines and processing facilities are presented in other reports (e.g., UNSCEAR, 1993; Mudd, 2008). The NRC (1986) reviewed existing information regarding the potential for radon and radon decay particle release from uranium tailings, and noted that the relationship between the concentration of radionuclides in a tailings pile and the radon flux from a pile is complex and, moreover, the relationship has considerable variability by site. Although modeling can serve a role, overly heavy reliance should not be placed on general models of radon emission and dispersion without site-specific information. More recently, UNSCEAR (2009) also recognized that significant deviations of selected model parameters (e.g., population density, emission rates) are possible, and that while careful management of tailings in the future would be expected, variations in management of tailings could result in increases or decreases of estimated exposures by at least an order of magnitude. In concluding their section on mining and processing dose estimates, the UNSCEAR (2009) report indicates that, "*Further surveys of site-specific conditions would be useful to establish realistic parameters for the worldwide practice"* (UNSCEAR, 2009, p. 182).

Because of the complexity and variability of factors that affect off-site releases (e.g., site characteristcs, deposit type), as well as the variations in assumptions used by the investigators, the magnitude and geographic distribution of off-site exposure to radon and its decay products are difficult to quantify (UNSCEAR, 1993, 2009; Chambers, 1998a,b; Frost, 2000; Mudd, 2008). Accurate radiation exposure estimates specific to the Commonwealth of Virginia that could be used for reliable modeling, as well as risk estimates for off-site populations (i.e., nonmine or nonprocessing facility workers), would require information (e.g., source data, site characteristics, and operational specifics) that does not currently exist. Clearly, additional site-specific research would be required to develop baseline

data and methods to assess the long-term potential for releases of radon and its decay products to the population in the adjacent environment. Compared with radon progeny exposure leading to alpha particle exposure, off-site gamma radiation exposure is generally only a concern for individuals in close proximity to uranium tailings.

URANIUM HEALTH HAZARDS

As noted previously, among the three naturally occurring uranium isotopes (^{238}U, ^{235}U, and ^{234}U), ^{238}U exhibits greater than 99 percent relative abundance (ATSDR, 2011). Long-lived ^{238}U alpha-emitting decay chain radionuclides that are found in the suspended ore dust in uranium mines include ^{234}U, ^{230}Th, ^{226}Ra, as well as ^{210}Po with a half-life of 140 days. The relative contribution of these isotopes to the total lung dose of alpha particles is presented elsewhere (Harley et al., 1981; Harley and Fissenne, 1985). The decay products of uranium (e.g., ^{230}Th, ^{226}Ra) provide a constant source of radiation in uranium tailings for thousands of years, substantially outlasting the current U.S. regulations for oversight of processing facility tailings. When uranium is incorporated into the body, the primary radiological concern is from the emission of alpha particles, the radiation characteristics of which have been discussed previously in connection with radon. Regulations regarding exposure to uranium (described in Chapter 7) are prompted primarily by its chemical, rather than radiological, characteristics.

Uranium Absorption, Distribution, and Excretion

Internal exposure to ^{238}U can occur via inhalation, ingestion, or entry through a cut or other disruption to the skin. Dermal absorption of soluble forms of uranium through intact skin is also possible, but this pathway of exposure is not considered significant. The rate of inhalation and transport of airborne uranium within the body depends on both the particle size of the aerosol and the solubility of the uranium compound. For example, soluble forms of uranium (e.g., UF_6, UF_4, and $UO_2(NO_3)_2$) have moderate rates of absorption entering the bloodstream, followed by transportation to the kidneys and other organs (IARC, 2001). The majority (over 60 percent) of uranium in the blood is filtered in the kidneys and excreted in urine within 24 hours. Uranium compounds that are less soluble (e.g., UO_2, U_3O_8) tend to be retained in the lungs and tracheobronchial lymph nodes for many months or years, thereby creating an increased cancer risk from alpha particle exposure.

There is no conclusive evidence that uranium produces cancer in humans (ATSDR, 2011). Although uranium has not formally been classified as a human carcinogen by the International Agency for Research on Cancer (IARC), uranium-238 is considered a Group 1 carcinogen under the category of alpha-particle-emitting, internally deposited radionuclides (IARC, 2011).

Gastrointestinal absorption of uranium, with reported absorption rates that vary widely from 0.1 percent to 31 percent (Hamilton, 1972; Wrenn et al., 1985, 1989; Harduin et al., 1994; Limson Zamora et al., 2003), is affected by the solubility of the uranium ingested and previous food consumption (Sullivan et al., 1986; La Touche et al., 1987). The International Commission on Radiological Protection-69 (ICRP, 1995) model for the fate of uranium after it enters the bloodstream is based on both human and animal data. The model predicts that 12 percent of the uranium in the bloodstream is apportioned to the kidneys, 2 percent to the liver, 15 percent to bone, 1 percent to red blood cells, 30 percent to soft tissues with rapid turnover, 6.7 percent to soft tissues with intermediate turnover, and 0.3 percent to soft tissues with slow turnover rates. The ICRP-69 model also predicts that 63 percent of the uranium that enters the blood is promptly excreted in urine via the bladder, as noted previously (Royal Society, 2001). According to the ICRP (1995), of the uranium that is retained, 66 percent is deposited longer term in the skeleton, 16 percent in the liver, 8 percent in the kidneys, and 10 percent in other tissues. IARC (2001) notes that a portion of uranium deposited in skeletal bones may remain there for over 20 years, which poses a risk for cancer of the bone and leukemia. Additional information on uranium occurrence, routes of exposure and entry into the body, deposition, and clearance is presented in detail elsewhere (ICRP, 1991, 1995; Leggett, 1994; NRC, 1999b, 2008b; Royal Society, 2001; Brugge et al., 2005; ATSDR, 2011).

Adverse Health Effects of Uranium

Uranium has no known normal metabolic function or essential human elemental requirement. It has been shown to cause chemical toxicity, and because it emits predominantly alpha particles, uranium is a suspected human carcinogen (ATSDR, 2011). The Agency for Toxic Substances and Disease Registry (ATSDR) recently published a detailed review of adverse uranium health effects (ATSDR, 2011), concluding—as have other reviews—that the primary effect from uranium exposure is renal toxicity. Soluble uranium compounds and uranium compounds that become soluble by forming a bicarbonate complex in the blood can produce impairment of the proximal tubules (ATSDR, 2011); renal toxicity associated with high doses of uranium can lead to death. However, if the renal tubular epithelium is damaged by acute or chronic lower level exposures, it can usually regenerate. ATSDR (2011) did not identify any human studies that assessed health effects of dermal exposure, as opposed to ingestion, of uranium.

The USEPA has set a maximum contaminant level of 30 µg/L for uranium in drinking water, as well as a maximum contaminant level goal of no uranium in drinking water, based primarily on its chemical toxicity (USEPA, 2012a). Several epidemiological studies have used aggregate data (Mao et al., 1995; Limson Zamora et al., 2009; Seldén et al., 2009) to examine potential adverse health

effects of chronic exposure to uranium in drinking water. These studies reported renal effects possibly related to the uranium exposures, but no dose-response findings were observed. Results from the aggregate-based studies (i.e., studies that examine aggregated data at the population level and lack information on disease or exposure for a specific individual) need to be interpreted cautiously and are generally used for hypothesis-generating purposes, rather than hypothesis testing, because of their potential for biases due to their lack of individual-level information on both exposure and disease. Numerous epidemiological studies of miners and processors (discussed below) have noted adverse renal effects associated with uranium exposures from inhalation. ATSDR (2011) also noted that several of these studies analyzed potential reproductive effects (i.e., damage to sex chromosomes) related to inhalation of uranium, but provided limited empirical evidence of such a relationship.

Experimental animal data concerning systemic adverse health effects from inhalation, ingestion, and dermal absorption of uranium are more robust. Animal studies have provided a rich dataset that characterizes the renal toxicity (e.g., reduced glomerular filtration rate, renal enzyme changes) of uranium under controlled experimental conditions (Vicente-Vicente et al., 2010). Nonspecific neurological symptoms also have been observed in animals that have been exposed dermally or via inhalation of high concentrations of uranium (ATSDR, 2011). Of note, despite its renal toxicity, there are no reported studies of ototoxicity from uranium in experimental animals, although this question could be highly relevant to uranium and noise co-exposed workers.

Occupational Exposures and Health Effects of Uranium

In part because of the low specific activity of uranium, the renal health effects and potential respiratory effects of uranium exposure are most often attributed to the chemical properties of uranium (ATSDR, 2011). The primary clinically observed health effect related to uranium exposure is chemical-induced nephrotoxicity. The first observations concerning the nephrotoxicity of uranium began in the 1800s, when uranium was intentionally administered as a medical treatment for diabetes and other diseases (Hodge, 1973). “Uranium nephritis” was described as early as 1915 (Oliver, 1915). Although the causal link between nephrotoxicity and uranium exposure was established many years ago, few epidemiological studies with rigorous exposure assessments and sufficient sample sizes have been performed that examine the risk posed by uranium to workers in the uranium mining or processing industry. Additional epidemiological data relevant to this question among uranium miners and processors will be provided in a later section on silica exposure.

Assessing the causal relationships between uranium exposures in miners and adverse health outcomes presents a challenge because of confounding by occupational exposures to radon decay products, silica, and diesel exhaust. Ura-

nium miners clearly have higher all-cause mortality rates compared with selected reference populations, and do not—as is the case with the majority of other retrospective occupational mortality studies—exhibit the tendency for workers to be healthier than the general reference population (i.e., the "healthy worker effect"). Boice et al. (2008) attributed this excess mortality to exposure to radon decay products, rather that uranium itself. In addition, data on lifestyle factors that will affect mortality risk (i.e., confounders), such as smoking and alcohol consumption, have not been available in many of the epidemiological studies for these cohorts, which precluded adjustment of these factors. As pointed out by the Royal Society (2001) report, only a limited number of epidemiological studies have been performed examining the adverse health outcomes of workers who work with uranium and even fewer studies have looked at nonfatal health outcomes. As noted previously in regard to extrapulmonary cancer risk from radon decay product exposure, the ability to observe work-related health effects is reduced when epidemiological studies rely solely on death certificates as a measure of health outcomes.

The potential for exposure to uranium, as noted previously, is highest during processing. Several retrospective cohort mortality studies of uranium processing workers where exposure to radon decay products is expected to be less than that of underground miners, although not negligible, have been performed. These limited studies have failed to establish a consistent pattern of excess mortality among uranium processing workers (Archer et al., 1973a; Pinkerton et al., 2004; Boice et al., 2008). Findings from these studies related to silicosis are discussed in a following section. These studies, especially Archer et al. (1973a) and Pinkerton et al. (2004), should be interpreted with caution because of the limited sample size and lack of individual measures of exposure and smoking data.

Other sources of epidemiological data are important for assessing the potential health effects of occupational exposure to uranium itself. These data sources are needed because adverse health effects seen in mortality studies of underground uranium miners are dominated by radon-related exposures, and because studies of uranium processors have been limited by small sample sizes and poor exposure assessment. Thus, findings from the wider uranium industry are particularly relevant to the question of potential uranium-specific adverse health effects from uranium mining and processing. The findings from two systemic analyses of multiple epidemiological studies are described in the following text. These two analyses, by the Royal Society and the National Research Council, are summarized in this report because—despite their many limitations—they are the most scientifically rigorous data analyses that have been performed to date on this subject and often serve as the predominant findings referenced indicating that uranium exposure to workers does not infer a substantial adverse health risk.

The meta-analysis (i.e., an analysis that represents a combination of other analyses) performed by the Royal Society (2001) is particularly noteworthy. It included 14 studies (11 from the United States and 3 from the United Kingdom),

and examined the adverse health effects associated with work in the wider uranium industry—including uranium processing, uranium enrichment, uranium fuel fabrication, phosphate fertilizer production, and employment at other uranium-contaminated sites. This review included approximately 120,000 workers with 33,000 observed deaths. Health outcomes included all-cause mortality, deaths from 13 specific cancer types, and from genitourinary disease as a primary cause of death. The authors of the meta-analysis noted selected risk elevations in individual studies, including increases in overall mortality (Frome et al., 1997; Ritz, 1999), kidney cancer (Dupree-Ellis et al., 2000), Hodgkin's disease and bladder cancer (McGeoghegan and Binks, 2000), lung cancer (Frome et al., 1997; Ritz, 1999), prostate cancer (Beral et al., 1988), and a statistically significant dose-response relationship between internal lung dose and upper aerodigestive tract cancers as well as haematopoietic and lymphatic cancers (Ritz et al., 2000). The meta-analysis combining these studies nonetheless did not observe statistically significant increases in all-cause mortality, all cancer mortality, or mortality due to specific cancers, or genitourinary disease (a category that included kidney dysfunction). As the Royal Society (2001) researchers pointed out, the meta-analysis had numerous limitations, including lack of uranium exposure data, potential double counting of subjects that were common to more than one study, inclusion of subjects with little or no uranium exposure, lack of exposure information on toxicants other than uranium, and the tendency for workers to be healthier than the general reference population (i.e., healthy worker effect). Because of these limitations, the authors of the Royal Society report concluded that—based on the meta-analysis—it would not be justified to infer that adverse health effects associated with occupational uranium exposures do not exist.

The National Research Council (NRC, 2008b) also performed a review of uranium worker epidemiological studies that overlapped somewhat with the Royal Society's (2001) earlier review. The NRC (2008b) report also noted many of the same limitations of these studies, including the lack of uranium exposure data, limited information on potential confounders, and the potential for a healthy worker effect blunting the ability to observe adverse health effect associations. This meta-analysis of mortality outcomes among nearly 110,000 workers also detected no significant excess mortality due to cancer or renal disease. The NRC reported that the findings suggested that occupational exposure to uranium compounds does not support a conclusion that uranium compounds had a highly carcinogenic or nephrotoxic effect in this combined study population. Nonetheless, the NRC (2008b) report concluded that an increased risk of lung cancer due to the inhalation of uranium particulates cannot be ruled out, especially because alpha particles are known to be emitted by such dusts. ATSDR (2001) agreed that the existing studies of uranium workers do not provide compelling evidence that occupational exposure to uranium dust causes lung cancer. Nonetheless they note—reiterating what other researchers also have stated (Archer et al., 1973b; Howe et al., 1986)—that because of the concurrent exposure to radon and thoron

progeny, the studies of such working populations are inadequate for assessing the carcinogenic potential of uranium.

Other important information on uranium-associated adverse health outcomes in human populations is limited, especially for environmentally exposed individuals (ATSDR, 2011; Brugge and Buchner, 2011). This includes information regarding neurological effects, immunotoxicity, developmental toxicity, reproductive toxicity, genotoxicity, and, finally, whether children are more susceptible than adults to such effects if indeed they are present.

RADIUM HEALTH HAZARDS

Radium is a naturally occurring radioactive metal with chemical characteristics similar to calcium. As noted previously, there are four naturally occurring isotopes of radium, including radium-228 (^{228}Ra), radium-226 (^{226}Ra), radium-224 (^{224}Ra), and radium-223 (^{223}Ra). Radium-224, -226, and -228 and their decay products are classified as Group 1 carcinogens (i.e., known carcinogenic to humans) (IARC, 2001). Because of the relatively short radioactive half-lives of ^{224}Ra and ^{223}Ra of 4 and 11 days, respectively, as well as their lower relative abundance as compared to ^{226}Ra, these isotopes carry less occupational health risk than ^{226}Ra with its 1,600-year half-life (Figure 5.1). In addition, ^{228}Ra, produced in the ^{232}Th decay chain, is generally not considered a major health concern in uranium tailings as compared to ^{226}Ra, because of its lower relative abundance and much shorter half-life of 6 years (USEPA, 1983).

During uranium processing, a large percentage of the uranium is removed, leaving the majority of the decay products in the tailings. Thorium-230 (^{230}Th) is the immediate decay product following ^{234}U and is the longest-lived (i.e., radioactive half-life of 77,000 years) decay product remaining in the tailings. The ^{230}Th provides a constant source of ^{226}Ra (Figure 5.2), which in turn decays into radon (as previously discussed). In addition to the production of radon from ^{226}Ra during mining and processing operations, ^{226}Ra decay products (i.e., bismuth-214 and lead-214) (Figure 5.2) in the waste or tailings can produce significant gamma radiation hazard (USEPA, 1983) both in the processing facility as well as near waste areas or tailings. Gamma radiation has the potential to increase the risk of cancer to varying degrees for most tissues and organs (USEPA, 2011a). Because of its similarity to calcium, ingested ^{226}Ra tends to concentrate in bone. The International Commission on Radiation Protection estimates that about 15 to 21 percent of ingested radium is absorbed (ICRP, 1993).

Existing understanding of the potential adverse health effects related to ingested ^{226}Ra is based primarily on studies of radium watch dial painters who worked with radium in the early 1900s (Martland and Humphries, 1929). These painters would routinely place the paint brush in their mouths in order to get the fine tip needed to paint the watch dials, which led to significant ingestion of ^{226}Ra which was followed by systematic absorption and subsequent deposition into the

skeletal system. The primary adverse health effect in this group related to the high degree of ^{226}Ra ingestion was bone cancer (i.e., osteosarcoma) (Rowland et al., 1978; Stebbings et al., 1984; Rowland, 1994). The USEPA also noted that in addition to bone cancer, protracted exposure to inhaled or ingested ^{226}Ra is linked to increases in lymphoma, leukemia, and aplastic anemia (USEPA, 2011c). Studies directly assessing the risk posed by ^{226}Ra to miners and processors are lacking, in large part because of the inability to separately assess the effects of exposures to ^{226}Ra relative to exposures to other radionuclides.

Along with exposure to radon decay products, inadequate containment of uranium tailings most likely represents the highest potential source of radiation exposure, related to uranium mining activities, to the general public. Landa and Gray (1995) note that "due to its high radiotoxicity and affinity for accumulating in bones," ^{226}Ra is generally the uranium daughter product of "most concern in hazard assessments of water supplies and food chains" associated with uranium mining tailings. The stability of uranium mine tailings is an extremely important focus of industry best practices (see Chapter 8). In 1976, the USEPA set a maximum contaminant level (MCL) for a combined ^{226}Ra or ^{228}Ra concentration of 5 pCi/L in public water supplies. The USEPA estimated that if 10,000 individuals consumed 2 liters water each day at the MCL for 70 years, one additional death would be caused (USEPA, 2011c).

Radiation-Related Adverse Health Effects in the General Population Living Near Uranium Mining or Processing Sites— Limitations of Epidemiological Studies

The potential off-site (i.e., non-occupational) adverse health effects related to modern mining practices remains an area of great uncertainty. Several well-executed ecological studies have been performed that attempted to identify increases or decreases in mortality or cancer incidence related to exposures from uranium mining or processing operations (Boice et al., 2003, 2007a,b, 2010). The earliest study by Boice and colleagues (2003) compared the rates of cancer based on death certificates from Karnes County in Texas, which had three processing facilities and over 40 mines that were in operation for various periods between 1961 and the early 1990s, to mortality-based cancer rates in "control" counties as well as to the Texas and U.S. mortality-based cancer rates. The researchers reported that no unusual patterns of cancer mortality were detected, suggesting that the uranium mining and processing operations did not contribute to increased cancer rates in Karnes County.

Boice and colleagues used a similar study design to the Karnes County, Texas, study to examine the mortality and cancer risk posed by past uranium mining and processing operations in Montrose County, Colorado (Boice et al., 2007b) and for another study to examine the health risks for a population living near a uranium processing facility in Uravan, Colorado (Boice et al., 2007a). Except for

an increased risk of lung cancer among males that was attributed to occupational radon exposure (i.e., working in mines) by the authors, no statistically significant increases in cancer or mortality rates were detected. A more recent study by Boice et al. (2010) investigated whether incident cancer or mortality rates were elevated in the population living near uranium mining and processing activities in Cibola County, New Mexico. The researchers did not find any evidence that the operation of the uranium mines and processing facilities increased the cancer or mortality rates for the nearby population.

Boice et al. (2007b) pointed out that definitive causal inferences cannot be established from these geographical correlation studies. Geographical correlation studies are hindered by the lack of individual-level exposure data, and so everyone within a certain region is assigned the same exposure. In addition, other risk factors (e.g., cigarette smoking, alcohol consumption) are also based on grouped data, and so adjustment for confounding at the level of the individual is impossible (Brugge and Buchner, 2011). Although epidemiologists rely on the use of geographically based studies to generate hypotheses, ecological epidemiological studies lack the ability to test hypotheses. As stated in epidemiological terms by Morgenstern (1995), *"Despite several practical advantages of ecologic studies, there are many methodologic problems that severely limit causal inference, including ecologic and cross-level bias, problems of confounder control, within-group misclassification, lack of adequate data, temporal ambiguity, collinearity, and migration across groups."*

PRINCIPAL URANIUM MINING AND PROCESSING EXPOSURES OTHER THAN RADIONUCLIDES

Silica

Silica overexposure is a potential hazard whenever resource extraction such as mining (underground or open-pit) or ore processing involves silica-bearing materials. The geology of uranium-bearing ore deposits is such that typically concomitant silica exposure cannot be avoided during mining and processing uranium. Many of the known uranium deposits in Virginia occur in granites that contain silica.

The primary health-effect-relevant route of exposure for silica is via inhalation. The concentration of silica dust that is crystalline (as opposed to amorphous) and in the respirable range (particles up to 10 microns can reach the airways, and particles smaller than 5 microns penetrate deeply into the lungs) is considered to be the most important exposure metric, and health protective standards are recommended on the basis of these attributes (e.g., NIOSH, 1978). The specific sources of silica dust generation in mining and processing operations can include drilling (including test bores); blasting; shotcrete formulation (this can include the addition of fine particulate "silica fume") and application to mine surfaces; earth-

moving, excavating, rock hauling and transport; crushing, processing, and sifting; and in the handling of tailings or mining debris. Other occupational activities that are nonspecific to mining or processing, but which are likely to involve silica exposure in conjunction with various phases of a large mining and processing project, include concrete finishing, sandblasting, and infrastructure construction (e.g., road building). Any mechanical operation that breaks apart silica-bearing materials not only can generate respirable dust, but may also produce freshly fractured silica—a form of the mineral believed to be of particularly high biological activity.

There are multiple silica-caused adverse health outcomes, predominantly—but not exclusively—disorders of the respiratory tract. Chief among these is silicosis, a progressive, life-threatening, fibrotic lung disease. The lung tissue changes that are the hallmarks of this disease are distinct to silica exposure. Pathological examination of lung specimens, however, is not required to make a clinical diagnosis of silicosis, which is frequently based on the occupational exposure history, lung function studies (such a measures of airflow, lung volumes, and the diffusing capacity), and radiographic assessment (which can include computerized tomographic [CT] imaging).

Silicosis has been endemic to mining and quarrying operations involving silica-containing materials, including among workers in uranium operations located in multiple regions of the world. One of the largest occupational cohorts of silica-exposed uranium workers derives from the "Wismut" operation in the former East Germany, with an estimated labor force of 400,000 (Schröder et al., 2002). This cohort has already been alluded to in the previous section on radon. As is noted in the report of that study by Schröder and coinvestigators, working conditions were reported to be particularly poor between 1946 and 1956; operations ceased in 1990. By 1999, silicosis had been recognized among more than 16,000 former workers (this total also includes silicosis complicated by concomitant tuberculosis).

Other studies covering the same period have documented elevated risk of silicosis mortality in cohorts of uranium workers. Such risk is typically expressed as the ratio of mortality standardized to the general population. The standardized mortality ratio (SMR)[3] is a basic metric of epidemiological risk derived from mortality studies such as those done among uranium mining and processing cohorts. A recent report of further follow-up of the Colorado Plateau cohort (a large group study of former uranium miners from the U.S. Southwest) added

[3]An SMR value above unity indicates a risk estimate greater that the comparison population—a probability of less than 5 in 100 ($p < 0.05$) that the observed deviation from unity would be observed by chance alone is generally taken to indicate a statistically significance elevated SMR; this can also be presented as a 95% confidence interval [CI], indicating where the observed SMR falls statistically. Note that the unity value for an SMR can either be presented as a value of 100 or a 1, with an SMR of 150 equating to 1.5, if the 100 × convention is not used. The values that are presented here have *not* been multiplied by 100.

15 years of additional mortality follow-up data for the period 1991 through 2005, supplementing previous data for 1960-1990 (Schubauer-Berigan et al., 2009). This cohort has also contributed to the epidemiology of radon health effects discussed previously. For silicosis deaths, the SMR for whites in the 1991-2005 period was 64.7 and for American Indians was 33.3 (even higher than the elevated point estimates in the earlier period of 42.5 and 24.2, respectively). In total, there were 54 silicosis deaths, although there were 37 classified as other or unspecified pneumoconioses.

A large French cohort study of uranium miners has also reported silicosis mortality over a comparable time period (Vacquier et al., 2008). In that analysis, the SMR was 7.12, based on 23 silicosis deaths among more than 40,000 miners. This SMR point estimate, although elevated and statistically significant, is far lower than the U.S. estimated risk based on Colorado Plateau data. The lower estimate from France could represent statistical variation or could reflect a higher general population death for silicosis in France, reducing the SMR because the referent value used in the ratio was higher.

Another relevant analysis is that of a cohort of more than 4,000 Czechoslovakian uranium miners who had worked between 1948 and 1959 (Tomášek et al., 1994). In that cohort, among those with 25 or more years of follow-up, the SMR for nonspecified chronic respiratory disease (which would subsume silicosis, 60 deaths in total) was modest—but statistically significant—at 1.6 ($p < 0.001$).

Data on silicosis among uranium process workers, as opposed to uranium miners, are more limited. An updated analysis of 1,484 employees of seven uranium processing facilities in the Colorado Plateau—with nearly 60 years of follow-up from 1940 through 1998—presents a relatively robust database because of the size of the cohort combined with the duration of follow-up (this cross product is summarized as person-years; in this analysis, 50,000 person-years of follow-up). This cohort study is distinct from the miner cohort already described above, but was alluded to in the previous discussion of uranium health effects among processors. This analysis reported a statistically significant increased risk of all nonmalignant respiratory disease (SMR 1.43; 95 percent CI of 1.16-1.73 based on 100 observed deaths) and, within that category, an increased mortality risk for pneumoconiosis, including silicosis (SMR 1.68; 95 percent CI of 1.26-2.21) (Pinkerton et al., 2004). A study of a smaller subset of processors in another mining-processing cohort from New Mexico (718 who were included were likely to have been employed only as process workers without underground mining experience, also with up to 50 years' follow-up) did not observe a statistically significant mortality risk for all nonmalignant respiratory disease, although the SMR point estimate was elevated (1.22; based on 24 observed deaths); pneumoconiosis mortality risk was not reported separately (Boice et al., 2008). Of note, the pooled estimate of respiratory nonmalignant disease, which can be derived by taking the published values available from these two studies and adding them together (yielding 124 observed deaths due to non-cancer-related lung disease

and with only 89.9 such deaths expected based on population rates), yields an SMR of 1.38 (with an associated statistically significant 95 percent CI of 1.14-1.65, using a conservative statistical Poisson assumption of such deaths being rare events). This excess rate indicates that the risk of death from nonmalignant respiratory disease among these U.S. uranium processing workers was increased by nearly 40 percent.

Silicosis, in its classic form, is a chronic process that becomes clinically manifest more than a decade after initiation of first exposure. For example, an analysis of length of employment and onset of silicosis among Chinese workers exposed to uranium dust from 1956 to 2002 reported a mean time elapsed of 14 ± 8 years until diagnosis (Wu et al., 2004). That analysis also reported that among uranium "geological prospecting teams" the duration to disease onset was on average 4 years less than the 14-year interval noted above (10 ± 6 years), an observation that could be related to exposure differences between miners overall compared with the subset that worked as prospectors.

Earlier onset, more progressive silicosis associated with more intense exposure is sometimes termed "accelerated silicosis." Although accelerated and classic silicosis differ in time course, they are believed to represent the same underlying pathological process. In contrast, "acute silicosis" is a pathological entity that can arise relatively soon after initial silica exposure, is often rapidly fatal, and is pathologically distinct from classic silicosis. Acute silicosis was first well described pathologically in the 1930s (Chapman, 1932). Decades later, an unusual idiopathic disorder of the lungs, pulmonary alveolar proteinosis (PAP), was described (Rosen et al., 1958). Since then, a number of case reports and case series have underscored the role of silica in at least a subset of classic PAP cases. To further complicate categorization and the medical terminology that is applied to these disorders, this subset of disease is sometimes referred to as "silicoproteinosis." For example, in a review of 139 cases of PAP, approximately one-half had occupational exposures to various dusts, and 10 were clearly silica-exposed (Davidson and Macleod, 1969). A case report of a mine drilling machine operator whose exposure included work as a test driller may be relevant because it underscores that associated exposures need not be massive (Sauni et al., 2007). Acute silicosis or PAP specifically associated with uranium mining has not been reported.

As is implicit in data from the German uranium mining cohort that combines silicosis and silico-tuberculosis (Schröder et al., 2002), silica exposure increases the risk of tuberculosis infection. This effect is attributed to silica-related immune dysfunction, particularly in pulmonary macrophages. This risk applies to tuberculosis (i.e., infection with *Mycobacterium tuberculosis*), as well as to infection with strains of atypical mycobacteria that do not typically cause disease in immunologically intact individuals. Silico-tuberculosis refers to frank silicosis with tubercular coinfection. It has become well recognized, however, that silica exposure, even without radiographic evidence of silicosis, is associated with increased

risk of tuberculosis potent enough to warrant medication prophylaxis for this disease (Fielding et al., 2011). In the Colorado Plateau cohort, tuberculosis-related deaths manifested statistically elevated SMRs in the first study period (3.44 and 2.40 for Whites and American Indians, respectively), but no tuberculosis deaths were noted among Whites in the second follow-up period and only two deaths among American Indians (SMR 2.39, not statistically significant) (Schubauer-Berigan et al., 2009).

In the Czechoslovakian cohort, the tuberculosis SMR for those with ≥ 25 years follow-up was 3.6 ($p < 0.01$) (Tomášek et al., 1994). The lymph node burden of silica following exposure may explain this pattern of risk, as observed in a recent analysis of a sample number of cases from a histopathological autopsy archive of deceased German uranium miners (Cox-Ganser et al., 2009). Among 264 cases (enriched for the presence of lung carcinoma), only 98 (38 percent) were free of a substantial parenchymal lung tissue burden of silica; among the remaining 166, 52 had silica involvement confined to the lymph nodes. In areas with high endemic infection, the triad of HIV, tuberculosis, and silica exposure has emerged as a major public health challenge (Rees and Murray, 2007). Thus, assessment of the potential health burden of silica exposure among any already marginalized population should take into account the potential for these combined, interactive risks. This is relevant to socioeconomic gradients of health among disadvantaged populations within Virginia.

Silica is a Class I recognized human carcinogen by IARC criteria (IARC, 1997). Review of the extensive epidemiological dataset supporting that designation is beyond the scope of this summary. It is noteworthy, however, that although the analysis of silica-associated lung cancer risk in mining operations was an important part of the IARC review, these data generally excluded uranium-exposed workers, because this occupation involves exposure to radon decay products, a potentially confounding lung carcinogenic exposure discussed above. The sole exception was the inclusion in the IARC review of a lung cancer case-control study of radiographic silicosis in uranium miners from the Colorado Plateau (see Samet et al., 1994; IARC, 1997, Table 19, p. 108). Based on 65 lung cancer cases and 216 controls and adjusted for radon co-exposure, silicosis was associated with a 33 percent increased risk of disease (because of the study design, this comparison does not yield an SMR), but with wide confidence intervals, meaning that this increased risk was not statistically significant at the 0.05 level (odds ratio [OR] 1.33; 95 percent CI of 0.31-5.72). Since that time, however, there has been increased interest in analyzing the combined risk of silica and radon to assess a potential interactive risk for lung cancer. An analysis of lung cancer risk among workers from two Swedish iron mines—one with substantial radon co-exposure and the other with negligible radon—recently addressed this question (Bergdahl et al., 2010). That study supported the presence of lung carcinogenic risks for both silica and radon in the mine with higher exposure to radon. Although the authors did not discuss interactive affects, the relative risk of lung

cancer for the highest radon exposure category was 3.9 and for the highest silica category 1.9, while in the highest exposure cell for both, the estimated relative risk was 9.3 (e.g., greater than the 7.5 cross product and thus consistent with an effect that is more than additive alone). An analysis of lung cancer mortality in the German mining cohort observed an independent association with silica exposure, but also did not assess potential interactions (Taeger et al., 2008). That study, however, demonstrates the high degree to which silica and radon exposure can be intercorrelated (correlation $r = 0.72$ in that cohort), underscoring the potential analytical difficulties in studying this question of interactive effects.

Silica exposure, with or without frank silicosis, has been associated epidemiologically and in case reports with selected extrapulmonary disorders, in particular, collagen vascular disease and renal disease, including disorders with overlapping end-organ effects such as scleroderma (Ranque and Mouthon, 2010). There are no reports specifically analyzing the relationship of silica exposure to these extrapulmonary outcomes among uranium miners. Of potential relevance, the extended cohort analysis of the Colorado Plateau miners observed a three- to fourfold increased SMR for acute glomerulonephritis (a potentially life-threatening form of kidney disease) among Whites in both time periods studied; no deaths for this cause were reported among American Indians (Schubauer-Berigan et al., 2009). An additional analysis of end-stage renal disease (ESRD) incidence (as opposed to mortality) observed an elevated point estimate for the standardized incidence ratio (SIR) for nonsystemic ESRD, which would include glomerulonephritis, for both Whites and American Indians (1.4 for each), but neither was statistically significant. A similar SIR approach was taken in the analysis of Colorado Plateau uranium processors. In that cohort, the risk for all ESRD was reduced (SIR = 0.71), but was increased for ESRD of unknown etiology (SIR = 2.73); in both cases the confidence intervals were wide and did not exclude no-effect (Pinkerton et al., 2004). As was noted in a previous section reviewing potential uranium extrapulmonary effects, the potential for renal toxicity from uranium itself also represents a potential mechanism for adverse health outcomes in these cohorts.

Finally, silica exposure is associated with chronic obstructive pulmonary disease (COPD). This association, however, extends beyond silica itself to inorganic dusts more broadly defined. Dust exposure in underground mining (silica and coal dust) was found to be strongly linked to COPD risk in a systematic analysis that included exposure levels and smoking adjustment (Oxman et al., 1993). Since that pivotal analysis, a large number of epidemiological studies have emerged consistently supporting a causal association between employment in dusty trades and increased COPD risk (e.g., Balmes et al., 2003; Blanc and Toren, 2007). Limited uranium mining and processing cohort data support the more generally observed association of dusty trades with COPD. In the Colorado Plateau cohort study, COPD mortality among Whites was significantly elevated in both time periods (SMR = 2.07 and 1.85, respectively), although the authors of

that study speculatively attribute this finding to smoking rates among the cohort relative to the referent population data used (Schubauer-Berigan et al., 2009). In the Colorado Plateau uranium processor cohort analysis, emphysema mortality was elevated (SMR = 1.96, 21 deaths observed), but not chronic and unspecified bronchitis (SMR = 0.91; only 2 deaths were observed, indicating low study power to detect an association) (Pinkerton et al., 2004).

Because of the latency between initial exposure and silica-related diseases such as silicosis, lung cancer, and COPD, the epidemiological data summarized above represent exposure conditions that span decades. It is presumed that improved working conditions leading to reduced exposure account for the decline in silicosis mortality observed in the United States in the 1970s to 1980s, but it should also be noted that the years of potential life lost (YPLL) due to silicosis have remained relatively flat from the 1990s onward (CDC, 2008). Indeed, silicosis deaths continue to occur in the United States, and mining remains a major contributor to the problem. For example, among 1,416 persons 44 years and older in United States dying from silicosis during 1968-2004, one in five with occupation and industry data available was known to be a miner; moreover, two-thirds lacked any employment information at all, such that the mining contribution may have been even greater (Mazurek and Attfield, 2008). Also, arguing against attenuation of risk, mining morbidity data for U.S. coal workers' pneumoconiosis—for which there is better surveillance than silicosis—indicate that over the last decade, severe dust-related disease among miners has actually been increasing in the United States (Wade et al., 2011).

Silicosis has been linked to environmental sources of silica exposure among persons without a direct occupational risk. Moreover, ambient elevations in silica have been detectable downwind from sand and gravel facilities, an exposure source that may be comparable to open-pit mining or rock hauling and dumping processes (Dhiraki and Holmén, 2002). Government regulators have carried out formal risk assessments of the potential public health effects of ambient silica; for example, in 2005 the California Environmental Protection Agency Office of Environmental Health Hazard Assessment adopted a "Chronic Reference Exposure Level" for silica that was driven by such ambient exposure concerns. Of note, this level was based on silicosis, rather than cancer risk (California EPA, 2005). A number of other states also have ambient silica standards, some of which are more stringent than California's (Wisconsin Department of Natural Resources, 2011).

Diesel Emissions and Diesel Particulate Matter

Exposure to diesel emissions is particularly relevant to the potential health effects of uranium mining because such exposures are ubiquitous in modern mining environments. The use of diesel engines in metal and nonmetal mines in the United States expanded greatly in the 1960s and 1970s; even by 1976, it was estimated that 60 percent of underground noncoal mines had diesel equipment.

Diesel engine exhaust contains respirable carbonaceous particulates that adsorb organic chemicals, including the polycyclic aromatic hydrocarbons benzo[a] pyrene and 1-nitropyrene. These compounds are carcinogenic in rodents when administered topically or by implantation, an effect that has been attributed to lung "overload" (Mauderly et al., 1987). Research has also suggested that inhalation of high concentrations of whole diesel exhaust causes destruction of pulmonary defense mechanisms and promotes the development of lung adenocarcinomas in animal models, whereas at lower levels of exposure that do not interfere with pulmonary clearance, diesel exhaust does not appear to be carcinogenic (Mauderly et al., 1990). This observation has been interpreted to suggest that one possible mechanism for carcinogenesis associated with inhalation of diesel emissions might be particle overloading, with subsequent inflammation of the lung, rather that the mutagenic effects of the organic fraction of diesel exhaust. The body of the evidence, however, does not support a threshold mechanism for diesel-associated carcinogenesis (California EPA, 1998).

The health effects of diesel exhaust have been studied in numerous epidemiological studies of occupational groups exposed to diesel emissions, notably operators of diesel powered railroad locomotives, heavy equipment vehicles, trucks, and some buses. This evidence for lung cancer is most suggestive and has been reviewed and summarized by numerous agencies and individuals, notably the National Research Council (NRC, 1981), the International Agency for Research on Cancer (IARC, 1989), Schenker (1980), Steenland (1986), Muscat and Wynder (1995), Bhatia et al. (1998), and Hesterberg et al. (2006). Although the 1981 NRC study found no evidence for the carcinogenic effect of diesel exhaust in the epidemiological studies, by 1989, IARC concluded—based on its review of the evidence—that diesel exhaust was "probably carcinogenic to humans."

The most comprehensive and rigorous systematic review and meta-analysis of the epidemiological data was that conducted by Bhatia et al. (1998). Based on 23 case-control and cohort studies with adequate data for inclusion, these authors concluded that the epidemiological evidence supports a causal association between risk for lung cancer and exposure to diesel exhaust. The overall meta-estimate (weighted by precision of the individual studies) indicated an increased relative risk (RR) for lung cancer associated with occupational exposure to diesel exhaust of 1.33 (95 percent CI of 1.24-1.44). Importantly, this increased risk persisted for subanalysis by type of study, smoking status, and type of comparison group for cohort studies. A positive "duration of employment–response" pattern was observed in the studies that stratified by employment duration. Although there was considerable heterogeneity among the studies included, the overall consistency of results from the individual studies and the meta-analysis are consistent with a causal association.

Because a lot of mining equipment today is powered by diesel engines, diesel exhaust—including diesel particulate matter—poses risks for multiple adverse

health effects among workers thus exposed. This is particularly relevant to the confined environment of underground mining, but is also relevant to open-pit processes as well as to exposure from diesel-powered equipment used in other aspects of mine and process operations (e.g., heavy vehicle transport equipment). Moreover, in certain mining environments, simultaneous exposure to three occupational lung carcinogens—diesel, radon, and silica—may occur (Bergdahl et al., 2010). In addition to the potential risk of lung cancer, cardiovascular and acute and chronic pulmonary effects of diesel emissions have been documented (California EPA, 1998; USEPA, 2002).

Physical Injury

Mining presents a large risk of traumatic injury. The most common causes of fatal injury include rock fall, fire, explosion, fall from height, entrapment, electrocution, and mobile equipment injuries. Fatal injury can also be caused by underground mine flooding, collapse of bulkheads, and caving failure. Fatalities have largely remained constant at around 40 per year from 1988 to 2007 (Figure 5.6) (NIOSH, 2011).

Both the number and frequency of nonfatal injuries have been declining (Figure 5.7), although there were still over 7,000 injuries in 2007 out of a population of approximately 255,000 miners (NIOSH, 2011). In underground mines, the

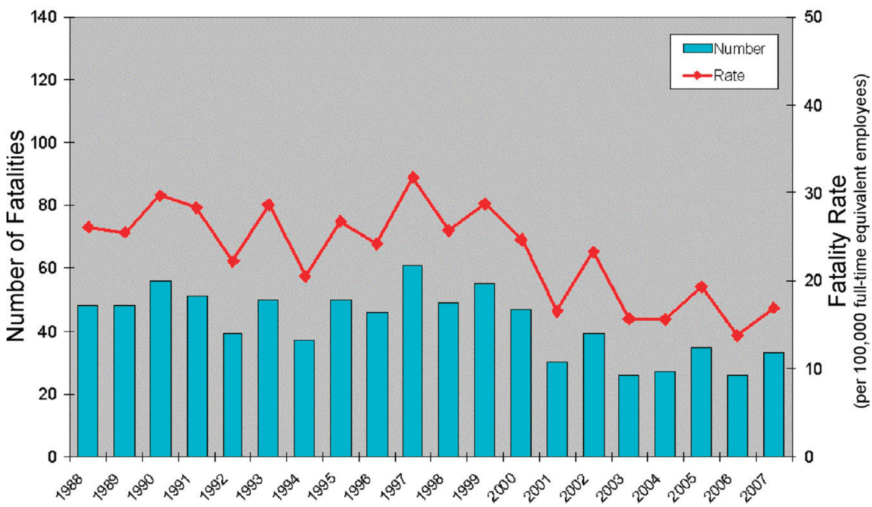

FIGURE 5.6 Number and rate of mining (including metal, nonmetal, stone, sand, and gravel mines) fatal injuries for 1988-2007. Office employees are excluded. SOURCE: NIOSH (2011), based on MSHA data.

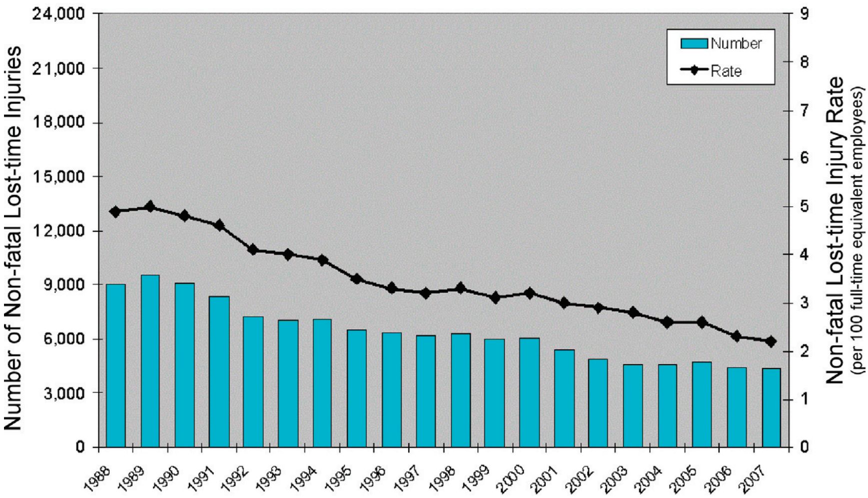

FIGURE 5.7 Number and rate of mining (including metal, nonmetal, stone, sand, and gravel mines) nonfatal lost-time injuries for 1988-2007. Office employees are excluded. SOURCE: NIOSH (2011), based on MSHA data.

largest injury category (~30 percent) over the 4-year period from 2003 to 2007 was materials-handling incidents. One way to judge the severity of nonfatal injuries is by the number of workdays lost; between 2001 and 2008 the average injury required 48 days of lost time before the worker could return to work, whereas between 1983 and 2000 the average number of lost workdays was 33. According to the U.S. Labor Department, the average number of lost workdays from injury for all other occupations was 8 days.

Electrical Hazards

As mine operators decrease their use of diesel-powered equipment in underground mines—to decrease exposure to diesel fumes—the need for additional high-voltage electricity to power equipment increases, increasing the potential for electrical accidents. Statistics indicate that in mines, electrical accidents occur less frequently than other sources of traumatic injury, but they are disproportionately deadly with a fatality rate of 1 in 22. Electrical accidents accounted for over 6 percent of deaths in mines between 2000 and 2009; a recent review indicated that electrical injury ranks fourth as the cause of death.[4] Compared with electrical injuries in other industries, mining is among the most dangerous.[5] There are vari-

[4]See http://www.cdc.gov/niosh/mining/pubs/pdfs/usbomn.pdf; accessed September 2011.
[5]See http://www.cdc.gov/niosh/mining/topics/topicpage1.htm; accessed September 2011.

ous causes of electrical injury in mines, and so a multifaceted approach is needed to mitigate electrical hazards. This would include engineering, administrative controls, protective equipment, and training to address human factors. One promising area of research involves a detection system for proximity to high-voltage lines.[6]

Noise and Vibration

Noise—Occupational Exposure

In 2007, the most recent year with data available on the NIOSH website (NIOSH, 2011), hearing loss or impairment was the second most prevalent reported illness among miners (after joint, tendon, or muscle inflammation or irritation). Overexposure to loud noise can cause temporary hearing loss by damaging the nerve cells in the cochlea of the inner ear. Although it is possible to recover from this temporary hearing loss, repeated damage to the nerve cells causes permanent sensory neural hearing loss.

Noise is also a safety hazard, because warning bells, whistles, or shouts could be masked by loud noise. The mining industry has the highest prevalence of hazardous noise exposure of any major industry sector (Tak et al., 2009). In a study of 31,325 uranium miners in Germany from 1946 to 1990, hearing impairment was found in 4,878 miners (16 percent) (Schröder et al., 2002). From 1991 to 1999, when noise controls were presumably in place, 129 of 4,619 miners (3 percent) had hearing impairment (Schröder et al., 2002). Uranium mining- or processing-specific noise-induced hearing loss data for the United States are not available.

As with any industrial safety hazard, minimizing exposure to noise through engineering controls is the best solution. A substantial amount of literature has been devoted to the engineering controls that have been designed to minimize noise from equipment such as pneumatic drills, roof-bolting machines, and other heavy equipment used in hard-rock mines. Plots of noise contours from common mining equipment have been compiled so that miners can predict the noise environment adjacent to such equipment. In the processing operation, rubber can be used in the machinery for crushing and grinding. This minimizes noise exposure and also provides reduced maintenance of equipment. If engineering controls are not practical, administrative controls—such as limiting the amount of time spent in the noisy environment—are an alternative solution. The last resort, after all other noise control measures have been tried, is to equip workers with personal hearing protection.

Standard computer programs are available to track worker noise exposure. Since uranium is a neurotoxin, it is possible that exposure to uranium, along with exposure to noise, increases the probability of noise-induced hearing loss (Janisch

[6]See http://www.cdc.gov/niosh/mining/pubs/pubreference/outputid3068.htm; accessed September 2011.

et al., 1990). MSHA has regulations that govern worker noise exposure, codified in 30 CFR Part 62. These regulations parallel OSHA noise regulations and have a permissible exposure level, action level, and hearing conservation program. There are requirements for periodic audiometric testing of workers as well as training.

Noise—Public/Off-site Exposure

Health effects of noise in a community setting are based upon speech interference and sleep interference, rather than noise-induced hearing loss. When ambient sound levels reach a level of 50 decibels (measured on the A-scale to simulate the human hearing range), they begin to mask normal speech (USEPA, 1974; Peterson, 1980). A speaker will have to raise his/her voice to be heard at a distance greater than 2 ft, and the listener will have to concentrate to understand the speech. Telephone use will be difficult, and consonant sounds will be difficult to distinguish. These speech interference effects may be considered a nuisance in a typical residential setting, but may be more critical in an educational setting. Although studies of noise reduction and its impact on student test scores suggest that there is an impact of reducing noise exposure on high school student performance, more study is needed on elementary and middle school children's performance (Eagan et al., 2004).

Sleep interference exhibits significant variability between individuals, and is linked to the subjective nature of the response. Much of the research on sleep interference has been conducted to study the impact of aircraft noise near airports (FICAN, 1997), and this indicates that a dose-response relationship can be drawn, despite the high degree of scatter in the data. To address the concern about sleep interference, model ordinances designed to protect the public against sleep interference generally require sound levels after 11 p.m. to be below 50 decibels, with an assumption that there will be 15 decibels of attenuation due to housing construction bringing the sound levels in sleeping rooms to 35 decibels. Although buildings can decrease sound levels by about 15 decibels through use of typical window construction, if the building is not air-conditioned and windows are opened during warm weather, sound is transmitted through open windows with no attenuation.

Noise—Physiological Effects

Noise can act as an environmental stressor, affecting the autonomic and hormonal systems, and causing elevated heart rate, blood pressure, and vasoconstriction. Prolonged exposure to noise can lead to chronic conditions such as hypertension and heart disease. The World Health Organization has reviewed the literature relating to physiological effects, and published community noise guidelines that cover all sources of noise (WHO, 1999).

At the federal level, USEPA or a designated federal agency regulates noise

sources, such as rail and motor carriers, low noise emission products, construction equipment, transport equipment, trucks, motorcycles, and the labeling of hearing protection devices (USEPA, 2012b). Primary responsibility for regulating community noise rests with states or local governments. In Virginia, some local governments have passed noise control ordinances, which are enforced by code enforcement officers.

During exploration for uranium, it is likely that there would be limited off-site community impacts. During construction, however, there are likely to be more off-site impacts due to drilling and earthmoving, and transportation of construction equipment could affect neighborhoods. The choice of mining technique will affect the noise contour of a mining facility, with open-pit mining having more neighborhood noise impact than underground mining. Processing (grinding of the ore) is a noisy operation, but the off-site impact might be minimal if it is a fully enclosed operation.

Vibration—Occupational and Off-site

Sound is the transmission of vibration in the audible range—from 20 Hz to 20,000 Hz—but energy present in the range below 20 Hz can still cause adverse health effects. Whereas sound is airborne, vibration is primarily structure-borne. Sources of vibration include construction equipment, drilling equipment, blasting, and processing (crushing/grinding) equipment. The health effects of whole-body vibration include fatigue, insomnia, stomach problems, headache, and "shakiness" shortly after exposure. Vibration reduction can be accomplished by using isolation and by installing suspension systems between the vibrating source and the operator. People who operate hand-held vibrating tools can experience changes in tendons, muscles, bones, and joints, and vibration can also affect the nervous system. These effects are known as "hand-arm vibration syndrome," and the symptoms are aggravated by exposure to cold. Ergonomic tool designs are available. Proper selection and maintenance of tools, and administrative controls, such as job rotation and rest periods, can reduce the adverse health effects (Nyantumbu et al., 2007; California State Compensatory Insurance Fund, 2011; Heaver et al., 2011).

Elastic waves emanate from any mining blast, causing ground vibration with potential to cause structural damage off-site. Most commonly, ground vibration causes lengthening of existing cracks. Without a structural failure leading to physical injury, however, this would not be classified as a human health effect. Humans can perceive potentially annoying vibration levels far below legal limits, but existing regulations are not intended to eliminate such annoyances.

MISCELLANEOUS HEALTH IMPACTS

There are additional potential exposures associated with uranium mining and processing beyond those individually described above. These can be categorized as either exposures arising generically out of mining (or at least the type of larger construction project that subsumes modern mining), or alternatively, exposures that are likely to be more specific to uranium processing and ore purification (although this latter category can overlap with certain related mineral extraction processes). Modern mining practices, in general, can be associated with a variety of hazards including—explosive gases; shotcrete; isocyanates; carbon monoxide; welding, metalworking fluids, and other maintenance-related exposures; and mold-related illness. In uranium processing, uranium extraction is a chemically dependent process, with certain commonly used substances (e.g., sulfuric acid) that are known to be hazardous, whereas other process chemicals have uncertain hazard status. A short description of these miscellaneous potential exposures is presented below.

Nitrogen Oxides in Explosive Gases

Beyond noise and physical trauma, explosive use produces nitrogen oxides as residues. Nitrogen dioxide inhalation can cause severe acute lung injury and lead to chronic lung sequelae, in particular a syndrome of airway destruction called “bronchiolitis obliterans” (Blanc, 2010). Exposure is likely to be highest in enclosed-space applications (e.g., underground detonations).

Shotcrete

The term “shotcrete” refers to various formulations of concrete-related materials used in high-pressure spraying applications. Shotcrete can be little more than a simple mix of cement and aggregate, which is associated with skin and eye chemical burns in mine spraying (Scott et al., 2009). In modern underground mining applications, however, shotcrete has evolved into chemical-intensive formulations that can include “plasticizers” to facilitate flow, accelerators to promote setting, and retardants to temper the accelerator effects, together with added fiber and finely ground silica fume (alluded to previously in the silica discussion). Shotcrete plasticizers can include ethylenediamine as an active ingredient. This organic chemical is a well-recognized sensitizer associated with asthma and dermatitis (White, 1978; Ng et al., 1991). Shotcrete accelerators can include diethanolamine [2,2′-iminodiethanol], also a sensitizing agent (Piipari et al., 1998; Lessmann et al., 2009).

Isocyanates (in Polyurethanes), Epoxies, and Related Reactive Polymer Chemicals

These materials are widely used in modern mining and tunneling techniques associated with bolt placement and other ceiling- and wall-stabilizing applications (Ulvestad et al., 1999). Exposure to these sensitizing materials can lead to asthma and probably carry risk of dermatitis as well (Nemery and Lenaerts, 1993).

Carbon Monoxide

Whenever internal combustion engine-powered equipment is used in or near enclosed or semienclosed areas, or with heavy outdoor use, excess carbon monoxide inhalation may occur (NIOSH, 1972). Exposure sources can include forklifts, gas-powered generators or compressors, gas-powered equipment, and motor vehicles. Air intakes near carbon monoxide sources can entrain the gas, leading to overexposure remote from the source. Motor vehicles can cause elevated ambient exposures to carbon monoxide (as well as diesel vapor and particulates as discussed previously) beyond the worksite itself, especially near heavily trafficked roadways or as a result of idling vehicles. Carbon monoxide can also be present in postexplosive detonation atmospheres, together with oxides of nitrogen (as described above).

Welding, Metalworking Fluids, and Other Maintenance-Related Exposures

Mining and processing operations require extensive onsite maintenance operations that include welding, machining, and various other equipment and parts maintenance and repair work. Welding exposures are complex, and a detailed summary is beyond the scope of this review. Note, however, that stainless steel and titanium welding (the latter because caustic process solution handling can require titanium alloys in working parts) can carry particular exposure risks, for example, from chromium, nickel, and titanium metal fumes (Antonini et al., 2004). These welding techniques can be routine work practices in uranium processing plant maintenance. Metalworking coolant fluid exposures are also complex, with health effects associated in particular with microbial contamination (Mirer, 2010). Other potential maintenance-related exposures include solvents, lubricants (including under high pressure), paints, and sealants.

Arsenic

Arsenic can be a common contaminant in uranium, as with many other metal-bearing ores. Based on existing knowledge of the uranium ore-bearing characteristics in Virginia (see Chapter 3), however, this does not appear to be a

relevant uranium processing exposure in handling locally mined ore. Were uranium processing to involve feedstock from other sites, the potential for arsenic contamination would require further assessment. In areas of the world where arsenic has been present as a uranium contaminant, exposure has been a major issue of occupational health risk among mining and process workers. Although arsenic is a potent toxin with a myriad of adverse effects, its carcinogenic potential has been particularly salient among uranium miners, in particular because of their concomitant exposure to radon (Taeger et al., 2008; Tomášek et al., 1994).

Other Metals—Vanadium, Selenium, Iron

Vanadium is commonly used as a catalyst in sulfuric acid manufacturing, which is often carried out on-site at uranium processing facilities. Exposure would be most likely to occur in the context of maintenance or catalyst replacement. The primary target organ for vanadium's adverse health effects in humans appears to be the airway, manifested by a bronchitis syndrome. In addition, IARC classifies vanadium as possibly carcinogenic to humans. Selenium can be a natural contaminant of mined materials and thus be a constituent of waste tailings; in addition to natural sources, iron can enter the waste stream as an intentional process additive. For both selenium and iron, the occupational toxic exposure potential does not constitute a relevant health risk in this industry, although such metals do pose a potential environmental hazard as is noted later (see Chapter 6).

Mold-Related Illness

Work activities that disturb soil, anticipated in any large-scale construction operation, have been associated with outbreaks of mold-related illness due to histoplasmosis or blastomycosis in areas where these environmental fungi are endemic. This could include parts of Virginia. Outbreaks occur among those directly involved in construction activities, but also among bystanders. In histoplasmosis exposures, bystanders have generally been adjacent (e.g., students attending a university with campus construction); however, at least one recent community-wide blastomycosis outbreak was linked to area-level roadway construction (Schlech et al., 1983; Carlos et al., 2010).

Sulfuric Acid and Sulfur Dioxide

Uranium processing can use either acid or sodium carbonate to dissolve (leach) uranium into an aqueous solution, as noted in the technical discussion of uranium extraction in Chapter 4. Acid extraction generally requires sulfuric acid in large enough quantities to require either onsite production or the transport of substantial quantities of the bulk product to the processing site. Sulfuric acid can also be used later in the processing sequence to "strip" uranium from its solvent

carriers (a mix of tertiary amines, decanol, and kerosene; see below), and in the treatment of process wastes and effluents ("effluent polishing"). Sulfuric acid production requires a source of sulfur that is handled through either a contact process or a wet sulfuric acid process. Both are associated with potential exposures, including sulfur dioxide, vanadium catalyst (as noted above), and sulfuric acid itself. Sulfuric acid skin contact, as might occur in a chemical spill, would be likely to lead to a chemical burn. Sulfur dioxide and sulfuric acid aerosols are both potent respiratory tract and mucous membrane irritants. Heavy acute exposure (e.g., through a leak or other large industrial release—events that can occur either as a result of on-site manufacturing or during transport from off-site) can cause severe lung injury; moderate acute exposure can lead to irritant-induced asthma (Blanc, 2010). Lower-level acute sulfur dioxide exposure—including area-level ambient air pollution, as might occur through inadequately controlled plant emissions—could be anticipated to cause asthma exacerbation, based on the known capacity of sulfur dioxide to induce increased airway resistance among persons with preexisting airway hyper-responsiveness, the basis for the health effects endpoint in U.S. National Ambient Air Quality Standards for this pollutant (Johns and Linn, 2011). Occupationally, sulfuric acid aerosol exposure is a known cause of chronic dental erosion. Epidemiological studies of sulfuric acid manufacturing worker cohorts have been limited to production processes in which the source of sulfur is sulfur contained in mineral ore.

Acrylamide and Related Polymeric Flocculants

These materials are used in uranium refining, together with mechanical separation techniques (e.g., countercurrent decantation and further clarification steps), to precipitate nonmetallic particulates from the process stream. Human-exposure-related adverse effects from polymeric flocculants, as relatively high-molecular-weight polymers, would not be anticipated among secondary occupational users (e.g., people involved in uranium processing) in contrast to the potential exposure risks among primary polymer manufacturers.

Tertiary Amines

Tertiary amines are used, with alcohols and kerosene, to chemically extract uranium from the aqueous solution that remains following the flocculation/decantation process. In this processing step, the uranium partitions into an organic solvent phase, while other metals remain predominantly in the aqueous solution (referred to as raffinate; see Chapter 4). The tertiary amines commonly used are either trioctylamine (which is widely known by the trade name Alamine 336, but also has other synonyms) or tridecylamine (Mackenzie, 1997). Both of these tertiary amines have similar chemical structures, with nitrogen linked to three identical aliphatic side chains of either 8 (octyl) or 10 (decyl) carbon atoms.

Toxicity data specific to these tertiary amine moieties are extremely limited. The Toxnet National Library of Medicine Toxicology Data Network lists only one human exposure study for trioctylamine and none for triodecylamine.[7] For the triodecylamine, a Russian study did not observe acute irritation to humans exposed by inhalation, even though mouse toxicity was observed not only when test animals were exposed by inhalation, but also by skin contact (Loyt and Filov, 1964).

As opposed to early steps in the uranium processing sequence, which can include open tanks with varying amounts of shielding, depending on the uranium concentration in the ore, solvent extraction typically takes place within a closed-circuit system. When used in such an enclosed system, occupational exposures are likely to be minimal under normal operating conditions, but excess exposure could occur in maintenance or quality control activities or through loss of integrity for an otherwise closed system (e.g., through a leak or other rupture). As solvents, these materials should be presumed to be readily absorbable through the skin, in addition to inhalation of vapor or through droplets suspended in the air. As a chemical group, aliphatic amines have been associated with causation of occupational asthma, indicating a structure–function relationship (Jarvis et al., 2005; Seed and Agius, 2010). Other tertiary amines have been shown to produce adverse ocular effects in exposed humans; the assessment of such endpoints, however, has not been reported for the specific octyl- and decyl-tertiary amines (Page et al., 2003).

Decanol

Decanol, a 10-carbon aliphatic alcohol, is used with the tertiary amines in the uranium solvent extraction process. Human health data specific to decanol are limited. It does penetrate intact skin and has been studied as a potential absorption enhancer in models of transdermal delivery for pharmaceuticals (Williams and Barry, 2004), even though in another study, it was found to be a human skin irritant (Robinson, 2002). In a rodent study, inhalation of decanol up to vapor saturation levels did not demonstrate sensory irritation (Stadler and Kennedy, 1996). In addition to being a synthetic organic chemical, decanol also falls within the category of microbial volatile organic compounds (MVOCs), produced as metabolites of fungi and detectable environmentally in sites of mold contamination—when 12 such MVOCs were tested in a lung cell-line model of toxicity, decanol proved to be the most toxic by a factor of 5 to 10 (Keja and Seidel, 2002). Decanol, along with other shorter chain aliphatic alcohols, was shown in a rat model to potentiate the liver toxicity of chloroform, even though decanol was not toxic on its own (Ray and Mehendale, 1990). Although questions of potential human toxicity are raised by these studies, the same imitated exposure scenarios in an enclosed system, as noted for the tertiary amines, are also relevant to decanol's application in uranium processing.

[7]See http://toxnet.nlm.nih.gov/; accessed September 14, 2011.

Kerosene

Kerosene is a hydrocarbon distillate of mixed hydrocarbon composition that is employed in uranium purification at the same process stage as tertiary amines and decanol (see Chapter 4). As noted previously, overexposure would only be likely to occur through perturbations in otherwise enclosed processes. Generically, adverse health effects of kerosene vapor inhalation or skin absorption are associated with higher level exposures, in particular through dermal contact leading to substantial systemic absorption (Bebarta and DeWitt, 2004). In addition, aspiration of petroleum distillates, as well as inhalation of their combustion products, is linked to acute lung injury (Blanc, 2010). These latter exposure scenarios, however, are not anticipated from the routine use of kerosene in uranium processing, although the latter is possible if there were to be a fire. Onsite storage of inflammable materials can be associated with risk of conflagration, and leaks of material at any stage of use (including stored material prior to use or in recycling systems or waste handling) can lead to groundwater contamination.

Sodium Hydroxide, Hydrogen Peroxide, and Ammonia

Sodium hydroxide (caustic soda) can be used in an alkaline process for the initial precipitant step after uranium is dissolved into solution, or it can be used to raise the pH of an acid solution in another processing stage (see Chapter 4). Industrial process solutions of sodium hydroxide are caustic and corrosive, requiring adequate skin and eye protection when handled and other safeguards against splashes, sprays, or aerosolization of concentrated solutions to prevent caustic eye, skin, or inhalation injury. Similar safety steps are relevant for high pH alkaline solutions (sodium carbonate/bicarbonate) if used in the initial process step of dissolving uranium.

Hydrogen peroxide can be used in both early and later uranium processing steps. In the initial leaching step, it facilitates solubilizing uranium by acting as an oxidizing agent (sodium chlorate and ferrous sulfate also can be employed as oxidants; adverse health effects would be limited to unlikely ingestion scenarios). Hydrogen peroxide can also be used as a reagent (along with magnesia) in the precipitation of aqueous uranium in its final purification as an alternative to sodium hydroxide or ammonia. Hydrogen peroxide at industrial concentrations (e.g., 50 percent or higher) is a powerful oxidant and highly irritating by inhalation, eye, or skin contact.

Ammonia can be used in uranium processing to neutralize acidified aqueous solutions containing uranium and precipitate the uranium. Concentrated (e.g., anhydrous) ammonia is typically handled in pressurized containers. Ammonia is an acute respiratory tract mucous membrane irritant that in high-level exposures can cause severe lung injury. Because of its high solubility, injury to the upper

airways, including the nasal tract, is particularly associated with ammonia inhalation episodes (Blanc, 2010).

For three of the agents discussed above (sodium hydroxide solutions, hydrogen peroxide, and ammonia), overexposure can occur through transportation mishaps if manufactured elsewhere and delivered for use, through storage containment failure, or through unintended release associated with valve or piping failure. Because pressurized ammonia is released as a gas (whereas the others are liquids), of the three, ammonia has the highest potential for inhalation injury in an acute system failure. In addition, unintended contact mixing of these materials, in particular hydrogen peroxide, with certain other reagents on-site can lead to potentially hazardous interactions. Adherence to internationally accepted best practices (see Chapter 8) should seek to minimize the likelihood of adverse events such as transportation mishaps or equipment failure that might lead to unintended releases of irritant or toxic chemicals.

FINDINGS AND KEY CONCEPTS

The committee's analysis of potential human health impacts that might apply if uranium mining and processing were to take place in Virginia has produced the following findings:

- ***Uranium mining and processing are associated with a wide range of potential adverse human health risks. Some of these risks arise out of aspects of uranium mining and processing specific to that enterprise, whereas other risks apply to the mining sector generally, and still others are linked more broadly to large-scale industrial or construction activities.*** These health risks typically are most relevant to individuals occupationally exposed in this industry, but certain exposures and their associated risks can extend via environmental pathways to the general population.
- ***Protracted exposure to radon decay products generally represents the greatest radiation-related health risk from uranium-related mining and processing operations. Radon's alpha-emitting radioactive decay products are strongly and causally linked to lung cancer in humans.*** Indeed, the populations in which this has been most clearly established are uranium miners that were occupationally exposed to radon. The epidemiological data from studies of radon-exposed miners clearly demonstrate that protracted radon decay product exposure causes lung cancer in a dose-dependent manner, and that it can act independently of other known carcinogenic exposures as well as having a greater than additive effect (i.e., synergistic effect) with co-exposures to other lung carcinogens (e.g., cigarette smoking). As protracted radon decay product exposure increases, so do the rates of lung cancer (i.e., a linear dose-response relationship). The existing scientific evidence indicates that even very low exposure to radon decay products

carries some risk, so there are incremental excess risks down to the lowest rates of environmental radon decay product exposure.

- ***In 1987, the National Institute for Occupational Safety and Health (NIOSH) in the Centers for Disease Control and Prevention recognized that current occupational standards for radon exposure in the United States do not provide adequate protection for workers at risk of lung cancer from protracted radon decay exposure, recommending that the occupational exposure limit for radon decay products should be reduced substantially. To date, this recommendation by NIOSH has not been incorporated into an enforceable standard by the U.S. Department of Labor's Mine Safety and Health Administration or Occupational Safety and Health Administration.***
- ***Radon and its alpha-emitting radioactive decay products are generally the most important, but are not the only radionuclides of health concern associated with uranium mining and processing.*** Workers are also at risk from exposure to other radionuclides, including uranium itself, which undergo radioactive decay by alpha, beta, or gamma emission. In particular, radium-226 and its decay products (e.g., bismuth-214 and lead-214) present alpha and gamma radiation hazards to uranium miners and processors.
- ***Radiation exposures to the general population resulting from off-site releases of radionuclides (e.g., airborne radon decay products, airborne thorium-230 or radium-226 particles, ^{226}Ra in water supplies) present some risk. The potential for adverse health effects increases if there are uncontrolled releases as a result of extreme events (e.g., floods, fire, earthquakes) or human error.*** The potential for adverse health effects related to releases of radionuclides is directly related to the population density near the mine or processing facility.
- ***Internal exposure to radioactive materials during uranium mining and processing can take place through inhalation, ingestion, or through a cut in the skin. External radiation exposure (e.g., exposure to beta, gamma, and to a lesser extent, alpha radiation) can also present a health risk.***
- ***Because ^{230}Th and ^{226}Ra are present in mine tailings, these radionuclides and their decay products can—if not controlled adequately—contaminate the local environment under certain conditions,*** in particular by seeping into water sources and thereby increasing radionuclide concentrations. This, in turn, can lead to a risk of cancer from drinking water (e.g., cancer of the bone) that is higher than the risk of cancer that would have existed had there been no radionuclide release from tailings.
- ***A large proportion of the epidemiological studies performed in the United States, exploring adverse health effects from potential off-site radionuclide releases from uranium mining and processing facilities, have lacked the ability to evaluate causal relationships (e.g., to test study hypotheses) because of their ecological study design.***
- ***The decay products of uranium (e.g., ^{230}Th, ^{226}Ra) provide a constant source of radiation in uranium tailings for thousands of years, substantially***

outlasting the current U.S. regulations for oversight of processing facility tailings.

- ***Radionuclides are not the only uranium mining- and processing-associated occupational exposures with potential adverse human health effects; two other notable inhalation risks are posed by silica dust and diesel exhaust*.** Neither of these is specific to uranium mining, but both have been prevalent historically in the uranium mining and processing industry. Of particular importance is the body of evidence from occupational studies showing that both silica and diesel exhaust exposure increase the risk of lung cancer, the main risk also associated with radon decay product exposure. ***Thus, workers in the uranium mining and processing industry can be co-exposed to several separate lung carcinogens, including radon decay products, silica, and diesel. To the extent that cigarette smoking poses further risk in absolute terms, there is potential for increased disease, including combined effects that are more than just additive.*** Moreover, because manual workers and lower socioeconomic status (SES) groups in the United States generally have higher rates of smoking, work-related lung cancer in uranium miners and processors may be related to socioeconomic status such that those with lower SES could comprise a particularly vulnerable subset of the population.
- ***Although uranium mining-specific injury data for the United States were not available for review, work-related physical trauma risk (including electrical injury) is particularly high in the mining sector overall and this could be anticipated to also apply to uranium mining. In addition, hearing loss has been a major problem in the mining sector generally, and based on limited data from overseas studies, may also be a problem for uranium mining.***
- ***A number of other exposures associated with uranium mining or processing, including waste management, also could carry the potential for adverse human health effects, although in many cases the detailed studies that might better elucidate such risks are not available.*** For example, some of the materials used in this industry may be potential sensitizers that could cause asthma. Many of these exposures have not have been adequately evaluated in animal or human studies.
- ***Assessing the potential risks of multiple combined exposures from uranium mining and processing activities is not possible in practical terms, even though the example of multiple potential lung carcinogen exposures in uranium mining and processing underscores that this is more than a theoretical concern.***

6

Potential Environmental Effects of Uranium Mining, Processing, and Reclamation

Key Points

- Uranium mining, processing, and reclamation in Virginia have the potential to affect surface water quality and quantity, groundwater quality and quantity, soils, air quality, and biota. The impacts of these activities in Virginia would depend on site-specific conditions, the rigor of the monitoring program established to provide early warning of contaminant migration, and the efforts to mitigate and control potential impacts. If uranium mining, processing, and reclamation are designed, constructed, operated, and monitored according to modern international best practices, near- to moderate-term environmental effects specific to uranium mining and processing should be substantially reduced.
- Tailings disposal sites represent significant potential sources of contamination for thousands of years, and the long-term risks remain poorly defined. Although significant improvements have been made in recent years to tailings management practices to isolate mine waste from the environment, limited data exist to confirm the long-term effectiveness of uranium tailings management facilities that have been designed and constructed according to modern best practices.

- Significant potential environmental risks are associated with extreme natural events and failures in management practices. Extreme natural events (e.g., hurricanes, earthquakes, intense rainfall events, drought) have the potential to lead to the release of contaminants if facilities are not designed and constructed to withstand such events, or fail to perform as designed.
- Models and comprehensive site characterization are important for estimating the potential environmental effects associated with a specific uranium mine and processing facility. A thorough site characterization, supplemented by air quality and hydrological modeling, is essential for estimating the potential environmental impacts of uranium mining and processing under site-specific conditions and mitigation practices.

This chapter presents a discussion of impacts of uranium mining and processing operations on air quality, soil, surface water and groundwater, and biota. Much is already known about the environmental impacts of mining, both on-site and off-site, and that body of information provides a basis for this chapter. However, the primary emphasis of the chapter is on the unique impacts caused by uranium mining, processing, and waste management. The committee sought out data from currently operating uranium mining sites, where available, although detailed publicly available environmental effects analyses were limited. As discussed in Chapter 4, the operating practices used in uranium mining and processing have evolved over recent decades, and by definition, there are no retrospective examinations of the environmental impacts of the most current practices. For this reason, this chapter provides a review of the accumulated evidence from prior studies of mining and processing at comparable sites around the world—especially data from several relatively recent decommissionings of uranium mines and processing facilities in Canada. The chapter includes analyses of impacts on surface water, groundwater, soil, and air and the ecological effects of these impacts.

ENVIRONMENTAL EXPOSURE PATHWAYS

Exposure pathways refer to the specific ways in which animals, plants, and people come in contact with environmental agents. In the case of uranium mining, processing, reclamation, and waste handling, exposure pathways to living organisms, including people, may exist for chemical and radiological materials via inhalation, ingestion, absorption through the skin, and gamma radiation

exposure. Gamma radiation is different from chemical contaminants because it can travel beyond the source, and direct contact is not necessary for exposure to occur. These pathways may be direct, as when someone breathes air that contains radon gas or dust, or may be indirect, as when a worm absorbs a chemical from the soil and the worm is eaten by another animal, which may eventually be eaten by other animals, including people. Exposures occur by eating, drinking, breathing, skin contact, or from gamma-ray emissions from radionuclides. Gamma rays can travel much farther than alpha or beta particles, and can penetrate the body, potentially exposing all of the organs. Radiation can easily penetrate solid materials such as soils or drums.

The exposure pathways are the same for people and for ecological resources, but different pathways are dominant. The exposures of greatest importance from the human health perspective are occupational exposures that occur within mines and enclosed processing facilities, primarily involving inhalation (see Chapter 5). Human health exposures may also occur in the surrounding communities if contamination travels offsite via air, surface water, or groundwater. Exposures of greatest importance for ecological effects occur outside the enclosed facilities, where radon and gaseous chemicals would quickly dissipate. The most significant exposure pathways for ecological resources are anticipated to occur via surface water because of its accessibility and the numerous potential transport mechanisms for dissolved and particle-associated contaminants (e.g., discharge of treated process water into streams; discharge of contaminated groundwater to streams). Such waters may contain chemicals, metals, and radionuclides higher than background or preconstruction conditions, particularly if treatment or waste containment systems fail to perform as designed. However, ecological exposures also may occur through air (e.g., dust, radon), contaminated soil, sediments, or from gamma radiation given off by radionuclides in contaminated materials.

SURFACE WATER EFFECTS

For purposes of description here, it is convenient to address surface water and groundwater as if they are separate entities, although the committee recognizes that surface water and groundwater are part of a single resource. Water moves between surface water and groundwater, and changes in the quantity and quality of one will affect the same parameters in the other.

Disturbances of the land surface associated with uranium mining in Virginia would be expected to have significant effects on both on-site and downstream surface water conditions. These disturbances affect both surface water quantity and quality. Many of these effects are similar to those encountered in other types of mining, although there are some unique risks posed by uranium mining and processing due to the presence of radioactive substances, and co-occurring chemicals such as heavy metals.

Impacts on Surface Water Quality

The disturbance of the land surface by mining, the temporary storage of ores and mining and processing wastes on-site, dewatering of mine workings/pits, and a variety of reclamation activities all have the potential to significantly affect the concentrations and loads of dissolved and suspended materials in surface water off-site. For purposes of this report, the materials of concern include some non-radioactive substances (especially dissolved heavy metals and metalloids), as well as naturally occurring radioactive materials (NORM), technologically enhanced naturally occurring radioactive materials (TENORM), and both solid and liquid tailings from processing operations. Considering Virginia's relatively wet climate, surface water would provide a principal vector for the off-site transport of contaminants.

Mining and Processing Effects

Acid mine drainage. Acid mine drainage (AMD) has the potential to be one of the most serious environmental problems caused by uranium mining in the Commonwealth of Virginia if it is not appropriately managed and mitigated. AMD is formed through oxidation of metal sulfides (e.g., FeS_2) present in the ore or waste materials by a group of acidophilic microorganisms (Campos et al., 2011). Because these bacteria thrive only under acidic conditions, the production of acidity can accelerate and become self-sustaining as long as sulfides and oxygen are available (Drever, 1982). Acidic mine water is more likely to contain heavy metals (e.g., iron, manganese, aluminum, copper, chromium, zinc, lead, vanadium, cobalt, or nickel) or metalloids (e.g., selenium or arsenic) released into solution by oxidation of the sulfide minerals, in addition to radionuclides in the uranium-238 (^{238}U) decay series (i.e., uranium, radium, radon, and thorium). Therefore, the presence of sulfide minerals in the uranium ore is a preexisting condition that promotes the release of radionuclides and toxic heavy metals from uranium mines to the environment. Analyses of the Coles Hill uranium deposit suggest that it is relatively low in sulfide minerals (0.04-0.05 percent; Marline Uranium Corporation, 1983), although other deposits in Virginia may contain higher amounts of sulfide.

Problems with AMD are nearly ubiquitous in the literature for uranium mines around the world, including sites in Australia (Mudd and Patterson, 2010), Germany (Biehler and Falck, 1999), Ontario, Canada (Berthelot et al., 1999), Saskatchewan, Canada (Waite et al., 1988), Portugal (Neves and Matias, 2008), and Brazil (Campos et al., 2011), as well as for virtually all types of mining (e.g., underground mining of high-sulfur coal deposits). It should be emphasized, however, that many of the documented problems with AMD are attributable to mines that operated at a time when environmental impacts were not an important consideration, and mitigation techniques were not widely employed. Yet, some of these sites serve as important examples of the significant surface water impacts

that can be caused by uranium mining and processing and of the efficacy of modern mitigation techniques that have been employed for the purpose of rehabilitating AMD-producing sites. In the following sections, several case studies of AMD mitigation from uranium mining operations at comparable sites around the world are examined.

The Rum Jungle uranium and copper mining project in Northern Territory, Australia, operated from 1954 to 1971, is an example of a mining operation that occurred with virtually no concern for environmental impacts. During early years of operation, mine tailings at this site were discharged onto a flat, low-lying area adjacent to the processing facility; about 0.26 million gallons per day (1 million L/day) of liquid tailings wastes were discharged to a nearby river, and the solid tailings proved highly erodible during wet-season rain events. A rehabilitation program from 1982 to 1986 aimed at reducing metal loads to surface waters included backfilling open cuts with tailing wastes, recontouring waste rock dumps, constructing engineered soil covers to limit infiltration and AMD production, and rehabilitating the former processing facility and ore stockpile areas. More than two decades following closure, a field campaign in the 1992-1993 wet season showed that concentrations of arsenic, chromium, copper, nickel, lead, uranium, and zinc still greatly exceeded water quality standards at a river monitoring station located 3.5 mi (5.6 km) downstream of the site. An important conclusion drawn from the field study is that despite extensive remediation efforts, AMD production and leaching of metals from waste rock dumps are a continuing cause of water pollution at this site, which has been attributed, at least in part, to a gradual increase in infiltration of water through dried and cracked clay soil covers over the waste rock dumps and subsequent AMD generation (Mudd and Patterson, 2010).

Mitigation of surface water quality effects from another early uranium mining operation that was active during the same period (1955-1996), at Elliot Lake in Ontario, Canada, had somewhat greater success while providing some important lessons for future uranium mining operations. As in the case of Rum Jungle, the relatively high mineral sulfide content of the ore and tailings at Elliot Lake provide a substrate for AMD production. During early mining operations, sulfide-containing tailings were dumped in a waste management area with no additional treatment. The tailings leachate with low pH and elevated metal and radionuclide concentrations led to declines in fish populations downstream (Clulow et al., 1998). Later, mine operators began using greater quantities of (1) lime to neutralize the acidity of the tailings and (2) barium chloride to precipitate the dissolved radium prior to wastewater discharge. Additionally, decommissioning of the Quirke mine at Elliot Lake in the 1990s employed a large-scale water cover (minimum depth of 0.6 m) over the waste management area to control the rate of sulfide oxidation and AMD formation, and site discharge was subsequently able to meet both Canadian and Ontario mine effluent guidelines. Although the mitigation activities have been deemed successful, one troubling result from a

long-term study of surface water contamination at the site is an increase in radium concentrations, which Peacey et al. (2002) attributed to barium-radium-sulfate dissolution. The regulatory authorities most familiar with this site have concluded that the decommissioned Elliot Lake uranium mine tailings "present a perpetual environmental hazard" making it necessary to keep the waste management area flooded and the water impoundment physically secure in perpetuity to prevent exposure of the tailings to oxygen, production of AMD, solubilization of thorium and radium, and release of dissolved radionuclides and various heavy metals to the downstream environment (CEAA, 1996).

Similar experiences occurred in the Athabasca region of Saskatchewan, Canada, associated with mining of the Gunnar uranium deposit in the vicinity of Langley Bay from 1955 to 1964. At this location, tailings were deposited into a small lake adjacent to Langley Bay, but a tailings dam failure in 1960 allowed the tailings to move into Langley Bay—a shallow body of water adjacent to Lake Athabasca—where they formed a deltaic deposit bisecting the bay. Some sampling locations in Langley Bay have consistently exceeded Saskatchewan water quality standards for ^{226}Ra, and further sampling has shown that the primary source of the contamination of the bay is from the periodic release of AMD from the tailings during snowmelt and rainstorm events. The sampling station closest to the tailings exhibited very high concentrations of both uranium and sulfate—consistent with this explanation (Waite et al., 1989).

Campos et al. (2011) has also reported low pH and high dissolved uranium and toxic metals concentrations in mine waters at the Caldas site, Minas Gerais state, Brazil (a pit mine operated from 1982 to 1995). Approximately 2 percent of the 95 million tons of rock removed from the pit were subjected to processing, with the remainder placed in two waste rock piles. In contrast to Rum Jungle, the Caldas mine utilized modern tailings and wastewater treatment facilities to collect and treat AMD from the waste rock piles as well as the acidic tailings; liquid and solid tailings were neutralized to pH 9 using calcium carbonate ($CaCO_3$) and lime (CaO) before being discharged to the tailings facility for solid deposition. Campos et al. (2011) and previous investigators identified the principal source of acid drainage at this site as the mine-waste rock piles, not from the tailings management facility. Campos et al. (2011) reported that following decommissioning, average concentrations of manganese, fluoride, uranium, zinc, and sulfate at several monitoring stations exceeded surface water quality standards. Thus, the authors further concluded that long-term use of the river waters downstream of the site that receive Caldas mine effluent needs to be very carefully evaluated.

Experiences from more recent mining projects demonstrate further improvements in the ability to mitigate surface water contamination from AMD. A decommissioning study of Cluff Lake in Saskatchewan, Canada, documents improved outcomes for a relatively modern uranium mining operation (1980-2002) but also reveals some continued environmental problems attributable, at least in part, to AMD (Box 6.1).

Newer mitigation strategies are perhaps best exemplified by tailings management at McClean Lake, Canada. Hydrological interactions between tailings liquid in the JEB tailings disposal pit and the surrounding groundwater system are minimized through the use of tailings compaction and a system of French drains to control groundwater head gradients. AMD formation in the Claude pit is minimized by disposal of AMD rock on a lined pad before it is returned to the flooded pit for disposal. AREVA Resources Canada, Inc. have suggested that the state-of-the-art McClean Lake tailings management facility has been able to maintain groundwater concentrations of dissolved nickel, uranium, arsenic, and radium-226 below regulatory limits.

Depending on their sulfide content, the disposal of mine spoils needs to be handled carefully to control or avoid AMD because the exposure of these materials to oxygen tends to promote acid-generating processes. During active tailings management, oxygen entry can be limited by maintenance of a water cover (Figure 6.2) over the tailings area. Also, liquid tailings and other wastewaters can be treated using lime and barium chloride to neutralize acidity, precipitate radium, and control dissolved metal and uranium concentrations prior to release to the environment. During the decommissioning phase, soil infiltration can be reduced using engineered soil cover materials of low permeability (e.g., clays) that can be riprapped and vegetated to provide protection against physical erosion. However, there are no data that document the long-term performance of these mitigation features.

If surface or underground uranium mining were conducted in Virginia, the extent of surface water contamination, including releases of both radionuclides and toxic metals, would depend on the mineral composition of the ore, the mitigative steps taken to minimize impacts to downstream receiving waters, and the long-term performance of those mitigative strategies under a variety of climatic conditions. Although the Coles Hill deposit has been reported to be relatively low in sulfide minerals, this may not be the case for all uranium ore deposits in Virginia.

Dewatering effects. To enable a mine to be worked, groundwater needs to be prevented from entering the mine or removed in a process known as dewatering. Groundwater entering the mine can be pumped out and discharged at the surface, or the local water table can be lowered using a number of extraction wells surrounding the mine to prevent water from entering. Mine dewatering activities have the potential to affect surface water quality, particularly if the discharge is not treated. Groundwater will naturally have a composition that reflects the mineralogy of the host rock and depends on many factors. As one example, uranium and ^{226}Ra concentrations in dewatering water from Cameco's Key Lake operation have ranged from 3 to 314 μg/L and 0.012 to 0.19 Bq/L, respectively, whereas at the McLean Lake mine the concentrations of these constituents have ranged

BOX 6.1
Cluff Lake Decommissioning Project

Perhaps the best available data on the environmental effects resulting from a modern uranium mine and processing facility are associated with the former Cluff Lake mine and processing facility, located in the Athabasca Basin of northern Saskatchewan, Canada, that treated high-grade ores ranging from 1 to 30 percent U_3O_8. Unlike most of the other mining operations that have been discussed in this section, uranium mining and processing at Cluff Lake didn't begin until the 1980s—an era in which environmental concerns were significantly enhanced and regulations were more stringent than in earlier periods. Two pits at Cluff Lake ("D" and "Claude") were mined first, followed by an underground mine ("OP/DP"), followed by three other pits ("DJN," "DJX," and "DJ"). All mining and processing at Cluff Lake ceased in 2002 after 22 years of operations, and with 62 million pounds of U_3O_8 produced. In addition to the mill, operational facilities at Cluff Lake also included a tailings management area with a two-stage liquid effluent treatment system and surface water diversion ditches, a residential camp area, and various other site infrastructure. Although tailings management and water treatment strategies have improved since the 1980s, the environmental assessment performed as part of the Cluff Lake decommissioning project provides a glimpse of what could occur if a modern uranium mining and processing operation were sited in Virginia.

A Canadian Nuclear Safety Commission (CNSC) environmental assessment to guide the decommissioning work was completed in 2003 (CNSC, 2003), and actual decommissioning was initiated in 2004. CNSC (2003) concluded that the primary environmental effects on completion of the decommissioning would be the migration of contaminants from existing sources (e.g., tailings and waste rock piles) to both groundwater and surface water. Most surface waters in the vicinity of the former mine/mill complex received no direct discharge and therefore were negligibly or only slightly affected by previous operations. Island Lake, however, was adversely affected because of its location immediately downstream of the mill effluent treatment systems. Measured mean annual concentrations of total dissolved solids, sulfate, chloride, uranium, and molybdenum in Island Lake in 2002 were two or three orders of magnitude higher than during the baseline (i.e., premining) monitoring period.

Acid mine drainage (AMD) from the Claude waste rock pile caused contamination of the Claude pit, resulting in greatly elevated levels of sulfate, total dissolved solids, uranium, nickel, arsenic, and radium-226. The relatively poor water quality of the Claude pit necessitated pumping water from the pit to maintain a water level below that of the adjacent lake to prevent transport of contaminants off-site. Groundwater has been similarly affected by AMD from the Claude waste rock, which has formed a shallow, acidic (pH < 4) groundwater plume with elevated levels of dissolved nickel (>10 mg/L) and uranium (>100 mg/L) migrating away from the waste rock pile.

Additional potential environmental hazards at the Cluff Lake site include the flooded mine workings and the tailings management area (Figure 6.1). The

continued

BOX 6.1 Continued

FIGURE 6.1 Tailings management area at Cluff Lake in 1999, Saskatchewan, Canada. The tailings are held behind an earthen dam. SOURCE: AREVA Resources Canada, Inc.

from 0.5 to 9.9 µg/L and 0.01 to 0.05 Bq/L.[1] Van Metre and Gray (1992) showed that dewatering an underground uranium mine located near Gallup, New Mexico, increased dissolved gross alpha, gross beta, uranium, and radium activities in the Puerco River from 1967 until 1986. Activities of the radionuclides declined rapidly once treatment of the water was initiated in the mid-1970s to bring the watercourses into compliance with the limitations specified by the National Pollutant Discharge Elimination System. Mine discharges into the Puerco River were subsequently treated with a flocculant and barium chloride to reduce total suspended solids concentrations and co-precipitate radium; dissolved uranium concentrations were reduced using an ion exchange treatment. To meet water quality standards, modern dewatering of uranium mines would provide for wastewater treatment prior to any release off-site.

[1]See http://www.bape.gouv.qc.ca/sections/archives/oka/docdeposes/documdeposes/DB86.pdf.

flooded underground mines represent a source of groundwater contamination and, if allowed to overflow, a potential surface water contamination source as well. The tailings management area was constructed as an unlined abovegrade facility, using an earthen dam to retain both solid and liquid tailings and enable chemical treatment of the mill effluent prior to discharge into Snake Creek and Island Lake. The tailings management area represents the principal on-site source of potential long-term environmental effects, although geotechnical evaluations of the earthen dam determined it to be stable, structurally sound, and in compliance with all design specifications. Given its location in a topographic low, constructed surface diversions were employed to isolate the tailings management area from the erosive effects of inflowing surface water.

A variety of mitigation options were considered as part of the environmental assessment process to address the remaining significant environmental issues at Cluff Lake with the explicit goal of minimizing long-term active mitigation activities (e.g., groundwater pumping, water treatment). Preferred mitigation strategies identified included (1) backfilling the pits with waste rock and capping with compacted till, (2) capping the Claude waste rock pile with a dry cover to minimize infiltration and AMD, (3) sealing of surface openings in underground mines to prevent overflows, (4) covering the tailings management area with a secondary layer of till, and (5) allowing natural recovery of Island Lake water quality. Although these options are likely to mitigate the remaining environmental problems at Cluff Lake to a significant degree, experience has shown that the environmental legacy of uranium mining is persistent over long periods of time. Monitoring and assessment (including a structured follow-up program to evaluate the performance of the mitigation strategies) will play an important role in guiding implementation of any additional mitigation at the site (CNSC, 2003).

Waste/Tailings Management

The effects of mine waste and tailings management on surface waters would depend on the amount and composition of the various waste materials, the methods used in processing the uranium ore, the ways in which the various waste materials are stored and disposed, and the steps taken to reduce the impacts on surface water quality. Mine and mill tailings contain all of the naturally occurring non-radioactive and radioactive elements found in uranium ore; these include all of the radionuclides in the uranium decay series, especially those of ^{238}U. Although 90-95 percent of the uranium in the ore is extracted during processing (thus reducing uranium concentrations by at least an order of magnitude), most of the uranium decay products (e.g., ^{230}Th, ^{226}Ra, ^{222}Rn), which may comprise the majority of the total radioactivity of the ore, stay in the tailings (Hebel et al., 1978, Van Metre and Gray, 1992). Because of the lengthy half-life of ^{230}Th (76,000 years), the activity of the tailings will remain essentially unchanged for

FIGURE 6.2 Waste management in the JEB pit at McClean Lake in Saskatchewan, Canada. SOURCE: AREVA Resources Canada Inc.

many thousands of years (Hebel et al., 1978). The geochemistry and mineralogy of ^{230}Th and ^{226}Ra (1,625-year half-life) are of particular importance from a water quality perspective, given their relatively long half-lives. Thorium is highly insoluble in aqueous solution under slightly acidic to alkaline conditions. The solubility of thorium increases in acidic aqueous solutions, and so tailings solutions can contain very high concentrations of ^{230}Th under acid-generating conditions. Radium in mill tailings can be adsorbed or co-precipitated with Fe-Mn hydrous oxides, gypsum, barite, or amorphous silica under oxidizing conditions, keeping ^{226}Ra concentrations in solution very low (Abdelouas, 2006). Although concentrations are reduced by processing, uranium is more mobile than either thorium or radium at near neutral pH under oxidizing conditions.

Uranium extraction using a strong acid leaching technique also tends to solubilize metals—the same process that occurs in AMD. Therefore, acid-leached tailings need to be carefully managed (e.g., neutralized and/or contained) to minimize the release of acidity, toxic metals, and radionuclides into surface water and groundwater environments. Modern tailings management sites are designed to remain segregated from the hydrological cycle for “1,000 years to the extent reasonably achievable and in any case for at least 200 years” to control mobility of metals and radioactive contaminants (10 CFR Part 40, Appendix A, Criterion 6(1)). If tailings are not emplaced in the mine workings as part of the

closure plan, then they are placed in an engineered disposal cell. In a relatively wet climate such as exists in Virginia, it is assumed that tailings would be stored in a saturated condition to minimize oxygen entry, sulfide oxidation, and mobilization of heavy metals and radionuclide elements from the facility (i.e., AMD). As shown at Elliot Lake and elsewhere, lined and capped storage repositories can prevent the spread of tailings by erosion and control contamination of groundwater and surface water systems from seepage (Peacey et al., 2002; Abdelouas, 2006), but no method of isolation is 100 percent effective nor has one been shown to be effective in perpetuity. Moreover, in a hydrologically active environment such as Virginia, with relatively frequent tropical and convective storms producing intense rainfall, it is questionable whether currently engineered tailings repositories could be expected to prevent erosion and surface and groundwater contamination for 1,000 years (Hebel et al., 1978). There are many reports in the literature of releases from improperly disposed tailings (e.g., Waite et al., 1988, 1989; Mudd and Patterson, 2010) and their environmental effects (Van Metre and Gray, 1992).

Full belowgrade disposal of mill tailings (Figure 6.2) is an option that has been developed specifically to eliminate concerns over the release of tailings due to catastrophic failure of a constructed retaining berm or tailings dam (see Box 6.2). Nevertheless, pending detailed site-specific characterization and engineering studies at potential uranium processing facility sites, the use of partially abovegrade tailings facilities cannot be discounted. For example, the Piñon Ridge uranium mill, the first new uranium mill in the United States in a generation, recently received license approval from the state of Colorado.[2] At that site, full belowgrade tailings disposal was considered the best option, but a partially abovegrade design with perimeter berms satisfied the relevant regulations and was recommended following detailed site-specific characterization.[3] Therefore, the potential hazard of a sudden release resulting from the failure of a constructed retaining berm remains. An aboveground tailings dam failure (e.g., due to liquefaction associated with a seismic event, an exceptionally high rising rate from local precipitation, improper spillway design leading to overtopping) would allow for a significant sudden release of ponded water and solid tailings into receiving waters (see Box 6.2). Such failure could necessitate aggressive remediation strategies, possibly including dredging, containment, and long-term water treatment. However, the committee cannot estimate the scope of possible remediation measures needed, because these would be dependent on site- and event-specific conditions. For more information on the remediation of radioactive wastes in the environment, see NRC (2009a,b, 2010) and USEPA (2008).

One of the most significant, if poorly publicized, tailings dam failures from

[2]See http://www.cdphe.state.co.us/release/2011/030711.pdf; accessed July 18, 2011.

[3]See http://www.cdphe.state.co.us/hm/rad/rml/energyfuels/application/licenseapp/tailings/rpt.pdf; accessed July 18, 2011.

BOX 6.2
The Virginia Beach Study:
A Preliminary Assessment of Potential Impacts of
Uranium Mining in Virginia on Drinking Water Sources

The Coles Hill uranium deposit and a number of other properties with former uranium leases (but unproven potential) are located upstream of Virginia Beach's drinking water intake, located in Lake Gaston. Lake Gaston is fed from the Kerr Reservoir which, in turn, is fed by the Dan, Bannister, and Roanoke Rivers in the Roanoke River Basin. The city of Virginia Beach commissioned a study (Baker, 2010) by the Michael Baker Corporation to *"model and estimate the water quality impacts from a storm-based breach of a uranium mill tailings confinement structure, which results in a large release of mill tailings downstream to the Banister or Roanoke rivers"* (Leahy, 2011). Notably, the statement of task did not ask the study to address the likelihood of such an event; it asked only for an analysis of the outcome assuming it did occur. Virginia Beach representatives made clear that the study simulated a "rare event that regulations are supposed to prevent" (Leahy, 2011). Although the Coles Hill property is encompassed by the study extent, the study was not specific to Coles Hill.

The final report, released in February 2011, summarized the results of nearly 200 model simulations. The scenarios differ by varying one of five primary input variables: tailings volume, sediment concentration by weight of the tailings, tailings particle size distribution, radioactivity level of the tailings, and flood hydrograph of the receiving surface water body. Both "sunny day" and extreme stream discharge scenarios were considered. Model parameter values were determined by researching the available literature because of the shortage of site-specific data for the area of interest. In particular, the authors relied on a study of tailings dam failures (Rico et al., 2008) and the empirical relationships derived therein to estimate outflow volume, run-out distance, and peak discharge. A comprehensive summary of the study is beyond the scope of this report but the key findings include:

- A tailings dam failure could significantly increase the radioactivity in the river-reservoir system for extended periods of time.
- Under such an event as simulated, the gross alpha concentration in Kerr Reservoir could remain above the USEPA maximum contaminant level (MCL) for several months or more.
- The model estimates that the majority of radioactivity entering the river-reservoir system remains in bed sediments over the simulation period of 1 year after failure. The remainder passes over Kerr Dam into Lake Gaston.
- Under such an event as simulated, uranium concentrations in the water column in Kerr Reservoir may temporarily reach or exceed the MCL of 30 µg/L.
- Reservoir operations affect the arrival and residence times of radioactivity in Kerr Reservoir.

Virginia Uranium, Inc. (VUI) commissioned Kleinfelder West, Inc. to review the Virginia Beach study (Baker, 2010) and made the results of that review available

BOX 6.2 Continued

to the committee in late June 2011. It was Kleinfelder's opinion that Baker did use appropriate methods and models in their study, but they questioned some of the assumptions of the study. Kleinfelder's largest criticism is that the initial assumption of a tailings dam failure as dictated by the statement of work is incorrect because (i) they estimate the probability of such a failure to be remote, and (ii) USNRC guidelines for disposal cell siting and design discourage abovegrade or partially abovegrade tailings disposal, while acknowledging that VUI is considering partially abovegrade disposal. As noted above, Colorado (an agreement state, see Chapter 7) recently approved and licensed a partially abovegrade tailings disposal design for the Piñon Ridge uranium mill even though fully belowgrade disposal was considered the best option.

a uranium mine/mill complex in the United States occurred near Church Rock, New Mexico, in June 1979. A breach of an earthen dam containing solid and liquid tailings caused the release of 1,100 tons of radioactive mill waste and 95 million gallons of mine effluents. It has been estimated that the breach allowed the release of 46 Ci of radiation—more than three times the release from the nuclear accident at Three Mile Island (Brugge et al., 2007). This spill illustrates the significant potential impacts from failure of an abovegrade tailings dam, reinforcing the desirability of belowgrade emplacement of tailings noted in Chapters 4 and 8, and in IAEA (2010).

Based on studies conducted at Elliot Lake, Canadian regulatory authorities identified several key factors that affect the capacity to adequately contain tailings waste in perpetuity[4] in modern tailings facilities (CEAA, 1996). These factors, which are highly relevant to uranium mining in Virginia, include drought episodes that could cause wastes to be exposed to oxygen; erosive effects of intense rainfall and flood events on dams, berms, or other physical impoundment structures; seepage and groundwater flow between the waste management area and the surrounding geological strata; and other natural disasters. Based on factors such as these, the Elliot Lake Environmental Assessment Panel concluded: "No containment system can totally preclude some release of contaminants" although the panel asserted that the Elliot Lake mitigative strategies "can hold the rate of release within acceptable limits" (CEAA, 1996).

[4]The government of Saskatchewan has established the Institutional Control Program for postclosure management of decommissioned mine and mill properties that requires "a detailed monitoring and maintenance plan for the management of the site in perpetuity . . . to ensure the site continues to meet the conditions specified at the time of entry into the Institutional Control Registry" (Saskatchewan Ministry of Energy and Resources, 2009).

The committee did not conduct a risk assessment for uranium mining in Virginia because a detailed site-specific analysis is beyond the committee's charge. The first step in assessing the risks associated with the release of contaminants from the uranium mine and mill would be to conduct a vulnerability analysis for security events and a risk analysis for natural disasters and other accidents. The consequences are not determined by the initiating event—they are determined by the design of the facility and whether the facility has appropriate spill prevention, containment, and countermeasures. The potential for long-term environmental effects requires a probabilistic risk assessment, driven in part by the inherent risks posed by the uranium mining, processing, and waste handling, but mitigated by the pollution prevention measures. A comprehensive risk assessment, including accident and failure analyses, is an essential step in any site-specific permitting decision. On the basis of an examination of published studies, the committee concludes that best practices, if properly implemented in association with rigorous monitoring, should address or allow the site operator to take action to mitigate the majority of short-term environmental effects from routine uranium-specific mining and processing activities. However, until site-specific risk and vulnerability assessments are conducted, the short-term risks associated with natural disasters, accidents, and spills remain poorly defined. If a major failure of waste containment facilities occurs, due either to extreme natural events or inadequate design, construction, or maintenance of such facilities, the potential long-term environmental effects are likely to be more than trivial. Temporary storage of mill tailings can pose greater short-term environmental risks, unless these facilities are also designed and constructed to contain the waste and treat all effluent under extreme climatic variability.

As discussed previously, waste rock piles, composed primarily of overburden or low-grade ore from either deep and/or surface mining operations, can also contribute to degradation of surface water quality (e.g., Rum Jungle, Cluff Lake). The disposal of waste rock is an issue in mining in general, because the volume of the mine voids cannot contain the entire volume of material removed during a mining operation; waste rock is typically stored in aboveground piles near a mine to minimize handling and disposal costs. Management of waste rock piles at uranium mines has evolved from the realization that all waste rock does not behave the same geochemically. The presence of metal sulfide minerals in portions of the waste rock is a cause of particular concern because of the possibility of AMD, and so proper characterization of the chemical properties of waste rock throughout the mining process is an important first step in addressing this potential hazard. Exposure of fresh mineral surfaces to oxygen during mining makes the waste rock more chemically reactive. Modern mitigation techniques for waste rock disposal would also include (1) careful siting of waste rock piles and construction of drainage ditches to facilitate collection of leachates; (2) isolation and burial of waste rock with high potential for contamination in low permeability strata to minimize interactions with water and air; and (3) if warranted, chemical

treatment of drainage water collected from waste rock piles. During decommissioning, soil covers can be used to control infiltration and production of leachate from waste rock piles.

General Mining Effects

Land disturbance by modern surface mining activities would be expected to increase the concentrations and loads of many dissolved and suspended nonradioactive substances in surface water, including some that are particularly important for water quality and aquatic biota: sediment, phosphorus, nitrate, metals, metalloids, and strong acidity. Elevated sediment loads are virtually ubiquitous in disturbed watersheds. In one of the most complete experimental studies in the literature, Bonta (2000), working on three surface-mined watersheds in Ohio, showed that sediment yields during active mining and reclamation activities increased by factors of between 46 and 1,310 relative to premining conditions. Use of diversions to reduce overland flow actually increased sediment loads because water that was concentrated in inadequately protected channels caused channel erosion or in other cases overtopped the diversions, causing rill and gully erosion. Reducing bare-soil exposure times reduced sediment yields, and sediment concentrations over the full range of measured flows were restored to undisturbed levels when diversions either were not used during reclamation or had been removed. In a comparative study of a reclaimed mineland and a forested control watershed in western Maryland, Simmons et al. (2008) showed that the mean sediment concentration from reclaimed mineland was approximately threefold higher than from forested watersheds. Comparable increases in sediment loads would be expected from surface mining for uranium in Virginia, but underground mining would not be expected to cause such impacts.

Concentrations and loading rates of many dissolved nonradioactive constituents in surface water (particularly sulfate) have been shown to increase as a result of surface mining of coal and subsequent reclamation (Bonta and Dick, 2003). Increases in the extent of surface runoff contribute to increases in constituent loads (load is the product of concentration and hydrological flux). The initial phases of mine reclamation can include additions of fertilizer, herbicides, and soil amendments that can also contribute to the contaminant runoff of the surface waters. Simmons et al. (2008) showed that the annual load of total phosphorus was a factor of 1.5 times larger from reclaimed mineland compared with forested watersheds.

Surface Water Quantity

Lands used for either underground or surface mining of uranium in Virginia would be expected to periodically discharge water off-site. The rates of discharge would be controlled by (1) precipitation inputs (e.g., rainfall inten-

sity), (2) antecedent moisture conditions, (3) land surface properties (e.g., soil infiltration capacity), (4) available water storage (e.g., detention ponds, pit storage), and (5) intentional releases of water from mining operations. Relative to unmined lands covered by native second-growth forests, surface runoff from lands disturbed by mining would likely be greater on-site. The relative increase in runoff would also cause increases in stream discharge in downstream receiving waters, although the percentage increase would be reduced with distance from the mines. The following sections explore the various impacts on surface water quantity from modern uranium mining and processing. These impacts per unit area disturbed would be comparable to those observed for other types of mining in Virginia, although the surface water quantity effects from tailings management could be greater.

Mining Effects

On-site and downstream surface runoff effects would be expected to vary depending upon whether mining is underground, surface, or some combination of the two. As a result of its smaller land surface footprint, underground mining would have the advantage of causing lesser impacts on surface water hydrology both off-site and downstream. The specific impacts associated with underground mining of uranium in Virginia are

- disruption (or total cessation) of spring flows and stream baseflow on-site due to blasting of rock (with *decreased* flows propagated to receiving waters downstream), depending on local geology, and
- increased flows in receiving streams owing to mechanical pumping of groundwater from underground mine workings (with *increased* flows propagated to receiving waters downstream).

Surface mining, on the other hand, would be expected to produce significant increases in surface runoff (especially stormflow) on-site relative to the unmined condition. Several field and modeling studies of surface mining for coal in the Appalachian Mountains of the United States have shown that rates of storm runoff generally increase (relative to a forested reference basin) with increasing mining activity in a watershed. Based on a field study of surface mining in Ohio in which both storm rainfall and runoff were measured, Bonta et al. (1997) showed that the "curve number" (a term describing the potential for surface runoff, with higher numbers reflecting greater runoff potential; NRCS, 2010) increased from a value of 76 for a premining condition to 87 during a period of active mining. As an example, for a 10-year, 24-hour event in Virginia that produces 6.0 inches of rainfall (Hershfield, 1961), this difference in curve numbers translates to a 36 percent increase in storm runoff (from 3.3 in to 4.5 inches of runoff) that is attributable to mining. However, caution is needed when extrapolating from coal

mining studies, because surface uranium mines are generally less extensive operations compared with surface coal mines.

Increased stormwater runoff on-site due to mining is mostly attributable to decreases in interception storage by vegetation and soil infiltration capacity because vegetation and soils are removed prior to mining of the rock (Ritter and Gardner, 1993; Bonta et al., 1997; Negley and Eshleman, 2006), although some additional effects are expected from road construction. Increases in stormflow could be modulated to some degree by utilizing the mining pit for temporary water storage, but typical sediment detention ponds provide little in the way of stormflow attenuation, particularly for extreme events. Stormflow increases would be expected to propagate to receiving streams downstream (with the local increase gradually attenuated farther downstream). Bonta et al. (1997) used flow-duration analysis to demonstrate that surface mining can also cause significant changes in baseflow levels in streams, but the changes were variable among the watersheds examined and a responsible mechanism could not be determined.

Numerous studies have shown that reclamation of a mine site does not dramatically reduce storm runoff (Ritter and Gardner, 1993; Bonta et al., 1997; McCormick and Eshleman, 2011). Negley and Eshleman (2006) showed that a reclaimed coal mine in western Maryland produced, on average, higher mean peak storm discharges and storm runoff depths by about a factor of 2-2.5 relative to a nearby forested reference watershed, despite the fact that only about 50 percent of the reclaimed watershed had been mined and reclaimed. Soil compaction resulting from the use of heavy, earth-grading equipment during the reclamation process dramatically reduces soil infiltration capacity and increases storm runoff. McCormick et al. (2009) and Ferrari et al. (2009) showed that local increases in storm runoff attributable to spatially distributed surface mining and reclamation in the Appalachian Mountains are propagated to receiving rivers downstream.

Waste/Tailings Management

The effects of the mine and mill tailings disposal on surface water hydrology would be similar to those associated with mining itself: greater storm runoff from disturbed land, including land previously mined and used for tailings disposal. Closed tailings ponds, however, would be expected to produce much greater storm runoff per unit surface area (because of the placement of impervious caps) than the forested land that they replace. Depending on the scale of the tailings management area, properly engineered, sited, and constructed tailings disposal areas would not be expected to significantly affect surface water hydrology. A tailings dam failure, however, would allow for a significant sudden release of ponded decant water into receiving waters, as discussed in the previous section (see Box 6.2).

GROUNDWATER EFFECTS

Groundwater fills the fractures in rocks and openings between mineral grains beneath the land surface and supplies wells, springs, and seeps (see also Chapter 2 and Figure 2.4 for a discussion of Virginia's groundwater resources and its use by Virginia residents). Numerous National Research Council reports detail the enormous challenges and remaining technological gaps associated with remediating groundwater contaminated with metals and radionuclides (NRC, 2008a, 2009a,b, 2010). Therefore, the design and use of effective mitigation measures to prevent contamination are preferred over relying on groundwater cleanup after contamination has occurred. In this section the potential effects of modern uranium mining practices on groundwater quantity and quality are discussed.

Groundwater Quality

Groundwater in contact with aquifer solids will attain a chemical composition that reflects the composition of the host rock through geochemical reactions. The extent of these reactions, and therefore the chemical composition of the water, depends on a number of geochemical and hydrogeological factors including but not limited to the mineralogy of the host rock, the mineral grain size, the chemical composition of the water passing through the aquifer, the residence time of the water in the aquifer, and flow pathways (e.g., fracture flow versus flow through granular porous media) (Cameron, 1978, 1980; Langmuir and Chatham, 1980; Rose and Wright, 1980; Giblin and Dickson, 1992; Leybourne and Cameron, 2006; Birke et al., 2009, 2010). Mining activities can alter several of these variables, consequently changing the quality of the groundwater. A carefully developed groundwater monitoring program with sufficient baseline data would be necessary to distinguish the effects of mining activities from existing groundwater conditions and naturally occurring concentrations of trace elements and radionuclides (discussed later in this chapter).

Exploration and Mining Effects

Uranium exploration efforts via systematic drilling to better define subsurface deposits has the potential to affect water quality, depending in part on the local setting, drilling methods, and how the boreholes are handled after completion. Installation of the borehole itself can alter the local geochemistry leading to the undesirable increased solubility and mobility of some elements. For example, introduction of oxygen into wells in eastern Wisconsin led to sulfide mineral oxidation and consequent decreased groundwater pH and increased concentration of sulfate, nickel, manganese, zinc, and arsenic (Schreiber et al., 2000; Gotkowitz et al., 2004). Similarly, introduction of oxygen into boreholes could oxidize poorly soluble reduced uranium(IV) minerals generating soluble and more mobile

oxidized uranium(VI) species. These effects are frequently limited to the local vicinity of the borehole itself.

Artificially connecting separate aquifers by drilling through confining layers or installing wells with long well screens can mix chemically distinct waters, which could result in the undesirable enhanced solubility and transport of elements that previously had been poorly soluble and immobile. Leakage of lower pH, oxygenated water from an unconfined upper aquifer into higher pH anoxic water in a lower confined aquifer through multiaquifer wells has been implicated as the primary cause for elevated uranium concentrations in a public supply well in York, Nebraska (Clark et al., 2008; Landon et al., 2008). Drill holes and mine shafts can serve as pathways for the upward migration of deeper saline water. Deep groundwater in some areas of Virginia is saline and, if under artesian pressure, would naturally flow upward to shallower depths if a conduit for flow were present. To protect groundwater quality, it is common practice for exploratory boreholes not completed as wells to be plugged with an acceptable material and abandoned, and Virginia exploration licenses typically require description of these actions by the applicant.

Many of the same potential impacts to groundwater quality described for drilling apply to underground exploration and mining; in particular, the effects of direct introduction of oxygen into the subsurface that can mobilize uranium and form acid mine drainage (as discussed previously), and the artificial connection of separate aquifers. Neves and Matias (2008) investigated groundwater quality in the vicinity of the abandoned Cunha Baixa uranium mine in central Portugal. Groundwater in wells downgradient from the abandoned mines showed degraded quality with elevated concentrations of uranium, copper, nickel, total dissolved solids, aluminum, manganese, iron, and zinc, which are characteristic of acid mine drainage. These processes have the potential of increasing the concentration of groundwater constituents above primary, secondary, or aesthetic standards (see Chapter 7).

Processing

Failures in on-site storage or accidents in the loading or transportation of chemicals used in the extraction process could result in a spill that infiltrates into the groundwater, resulting in groundwater contamination. Appropriate mitigation measures to minimize the impacts of such an event include administrative and engineering controls (e.g., access control, lock-out/tag-out procedures, secondary containment) and treatment, testing, and recycling of mill effluents prior to release to the environment. Treated effluent from operating Canadian uranium mills is below the screening objective of 100 μg/L uranium, with most below 10 μg/L (CNSC, 2010).

Waste/Tailings Management

Tailings from ore processing contain residual uranium, radionuclides from the uranium decay chain, and other chemical constituents associated with the ore or possibly with the milling process. Threats to groundwater quality related to modern tailings management originate from two sources: (1) failure of the structures designed to limit the movement of contaminants from the tailings into surrounding groundwater (e.g., tailings retaining structures, failure of the liners(s) and leak collection systems), and (2) inadequate hydraulic isolation in belowgrade disposal facilities (e.g., pump failure in active isolation, inadequate understanding of site hydrogeology, inadequate compaction of tailings in passive hydraulic isolation). Tailings disposal cells may be constructed specifically for that purpose or may be located in previously mined-out areas. As noted previously in this chapter, after uranium processing, the majority of the original radioactivity remains in the mill tailings after extraction of the uranium. The solid-phase concentrations of the radionuclides and co-occurring potential contaminants of concern (e.g., vanadium, arsenic) in the mill tailings will depend on the ore grade, site-specific mineralogy, and uranium extraction process (acid versus alkaline leaching). Additionally, the concentration they achieve in the tailings fluid will depend on water-mineral kinetic and thermodynamic constraints; changes to the chemistry of the tailings water can alter dissolved contaminant concentrations. Both dissolved and solids-associated contaminants in the tailings present a hazard to groundwater but the risk can be mitigated by recycling and treating water in tailings management facilities (see Chapter 4).

The method of tailings disposal will also influence the potential impacts of uranium mining and processing. Belowgrade disposal in a pit or abandoned mine workings would have the benefit of minimizing radon release and acid formation because the tailings could be covered with water. Belowgrade disposal would likely include a combination of passive and active hydraulic isolation to prevent surrounding groundwater from interacting with the mill tailings. Passive hydraulic isolation employs materials of contrasting permeability to direct water flow around rather than through the tailings. Active hydraulic isolation, similar to mine dewatering, uses a series of actively pumped wells to lower the local water table and maintain groundwater flow into rather than through or out of the tailings. If active hydraulic isolation is used, an important step would include sending the water for treatment at an on-site water treatment facility prior to releasing it to the environment.

Design for a tailings holding cell would include multiple barriers to minimize the risk of groundwater contamination. These barriers likely would include compacted clay overlain by two synthetic liners with a leak collection system placed between them, and engineering design criteria for tailings management would presumably be set forth in state regulations. Failure of the liner system could lead to large volumes of liquid lost relatively slowly over time without notice

unless or until detected in monitoring wells around the site. As discussed previously, tailings could be stored aboveground, partially aboveground, or entirely belowground. In the case of an aboveground or partially aboveground tailings facility, a tailings dam failure could lead to significant release of contaminated water. The fraction of water released that would recharge the aquifer and contaminate groundwater (as opposed to discharging to surface waters) would depend on several factors including topography, soil type, and antecedent soil moisture conditions.

To date, modern tailings disposal cells have been effective at preventing groundwater contamination (USDOE, 2010, 2011). Nevertheless, it should be stressed that currently none of these cells exceed 25 years in operational lifetime. So, while it is reassuring that the engineering designs have performed to expectation in the very near term, predictions on their behavior for the next 175 to 975 years have a high degree of uncertainty due to a lack of long-term performance data (NRC, 2007). In light of this uncertainty it is difficult to gauge the long-term risk associated with disposal cell leakage.

Groundwater Quantity

Operation of a uranium mine could be expected to affect groundwater quantity at the mine site with potential effects propagating off-site. Early phases of uranium mining (exploration and construction) would have negligible effects. However, during active mine operations, there could be significant effects on groundwater quantity.

Mining Effects

By lowering the water table to facilitate mining, mine dewatering can lower the groundwater levels in surrounding wells, possibly causing some nearby wells to go dry. Affected households would have to either drill deeper wells or find an alternate source of water. The extent of lowering of the water table is related to the volumetric rate of water withdrawn, aquifer permeability, and area groundwater recharge features (e.g., surface streams that recharge groundwater). This dewatering effect is greatest near the mine (or the dewatering wells) and diminishes with increasing distance. However, it is important to note that the effect can differ with direction from the well because of anisotropy in aquifer permeability (Figure 6.3). Under drought conditions, the difference between the water table at the mine site and unaffected groundwater levels decreases, because groundwater levels are lowered overall, reducing dewatering demands.

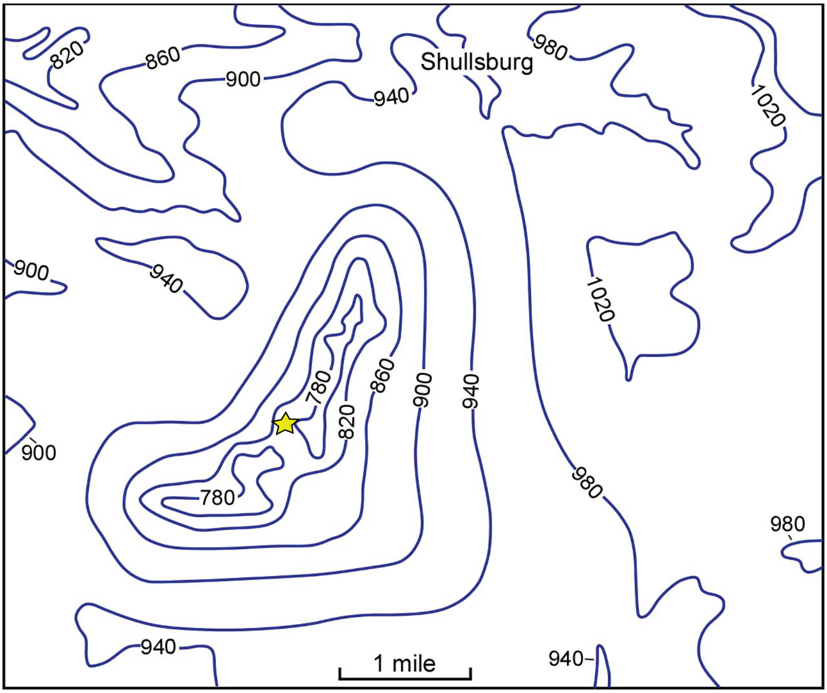

FIGURE 6.3 Measured potentiometric surface of the Sinnipee aquifer, southwest Wisconsin, during active dewatering of underground zinc-lead mines. Mines are located in proximity to the starred location in the left-center portion of the figure. The elliptical shape of the contours reflects anisotropic (direction-dependent) preferential flow along the diagonal from lower left to upper right. SOURCE: Modified from Toran and Bradbury (1988).

Reclamation and Postclosure

At mine closure, dewatering typically stops and mine workings are allowed to flood and groundwater and local water table levels will begin to rise. It could be many years to decades before water levels return to premining levels (Toran and Bradbury, 1988; Adams and Younger, 2001; Banks et al., 2010; Martinez and Ugorets, 2010; Caine et al., 2011). Additionally, because of mine construction disturbance to the aquifer, local groundwater flow patterns may be permanently altered, which could affect water supply for nearby domestic supply wells, although this effect is likely to be minor overall. Local groundwater recharge rates are also likely to be reduced as discussed previously in the section on surface water runoff. Finally, the decision to allow the mine to flood at closure, and under what conditions, needs to be carefully evaluated to prevent unintentional contami-

nation of groundwater. For example, backfilling the mine with low-permeability material prior to flooding can minimize groundwater flow though the abandoned mine works.

SOIL EFFECTS

Mining activity involves the removal of soil and overburden, which directly affects the physical, chemical, and biological properties of soil. The most common effects are loss of pore space due to compaction and changed soil structure, loss of permeability, changes in the ability of the soil to provide moisture for plant growth, loss of living organisms vital to healthy soils (e.g., microorganisms and earthworms), loss of viable seed bank with extended storage, loss of soil organic matter and nitrogen, and accelerated erosion. These impacts are not unique to uranium mining but are common to modern mining operations and large-scale industrial disturbance in general. These primary impacts are largely contained within the mining site, and the extent of soil impacts resulting from mining activities depends on the type of mining adopted. In the case of underground mining, impacts to soil are at a minimum because the surface disturbance is restricted to the relatively small underground entrances. In contrast, for open-pit mining the amount of disturbed soil is at a maximum. In addition, secondary effects, such as increased water runoff due to soil compaction, described previously in this section, can impact offsite conditions.

During mine site reclamation, topsoil that had been stockpiled during the mining process is replaced on the land. Reclaimed soils, however, are fundamentally different from natural soils in their physical, chemical, and biological properties, and some of these differences can take as little as 20 years or more than 1,000 years to recover. For example, stripping, stockpiling, and replacing the topsoil erases the natural soil horizons that develop over hundreds to thousands of years. Stockpiled topsoil deteriorates because of changes in the physical, chemical, and biological characteristics resulting from compaction, leaching, and degradation of the nutrients. Williamson and Johnson (1990) concluded that the nitrogen reserves in topsoil that was stockpiled and subsequently replaced were wasted because of changes in nitrogen cycling in those soils while they were stockpiled. Additionally, there were long-term changes to the microbial community (bacterial and fungal) of stockpiled soils that altered their function when used to restore mine sites relative to premining conditions or unmined areas (Johnson et al., 1991; Williamson and Johnson, 1991).

Reclaimed soils also tend to be compacted with an accompanying decrease in permeability and increased runoff (Marashi and Scullion, 2004). Sinclair and Dobos (2006) found that seven of eight reclaimed soils, varying in age from 6 to 17 years, had a lower land capability classification (LCC) relative to their premined condition. The primary factor responsible for the lower LCC in each case was a decrease in the soil's available water capacity—a measure of the

water a soil holds in a form available to plants. This suggests that reclaimed soils have degraded water capacity for long periods. Changes to the soil water capacity, coupled with changes to the chemical and microbiological properties of the reclaimed soil suggest that these soils would have lower long-term crop yields. Additionally, moisture stress will be a major factor dictating which plants will be successful on reclaimed soil. These differences in reclaimed versus pre- or unmined soils suggest that different soil management strategies for reclaimed soils would need to be in place for an extended period of time.

AIR EFFECTS

Citizens expressed concern about the air pollution and particulate matter that could be generated by a uranium mining and processing operation, and mobilization of contaminants by airborne mechanisms. Off-site transport of particulate matter causes nuisance effects, such as impaired visibility and dust accumulation on cars and houses. However, exposure to particulate matter can also lead to increased asthma, as documented by increased visits to emergency rooms, and even to death from heart or lung disease (Pope et al., 2009; Anenberg et al., 2010). People with increased susceptibility include infants, children, and adolescents; the elderly; people with respiratory conditions such as asthma, bronchitis, or emphysema; people with heart disease; and people with diabetes. The human health effects of airborne particulate exposures are described in Chapter 5; in this chapter, the committee describes the potential for off-site transmission of contaminants and air pollution effects on the environment at modern uranium mining and processing facilities.

Environmental and human health effects depend on a number of factors, including the chemical composition of the particles, the concentration, particle size and shape, and exposure time (IAEA, 2008). Distance of travel will be dependent on meteorological factors, particle size, and site conditions, among other factors. Depending on the size of the site and the dust control procedures implemented, there may or may not be off-site impacts. Large particles (>10 microns) settle out quickly from the air. However, to determine off-site human health and environmental exposure potential from dust (and particle-associated contaminants), meteorological modeling is essential. Modeling can be used to make estimates of the extent of particle transport under typical wind speeds and direction, as well under extreme weather conditions.

Uranium Mining and Processing

Mining Effects

Much of the dust caused by mining operations consists of fine particles that are generated from the mechanical disturbance of rock and soil, bulldozing, blast-

ing, and vehicles traveling on dirt roads. Particles can also be mobilized by wind blowing over ore stockpiles. Radioactivity monitoring at the fenceline, as well as at selected off-site locations can be used to verify the modeling predictions about off-site contamination. The Mine Safety and Health Administration (MSHA) requires radon monitoring of exhaust air from underground uranium mines for the purpose of estimating worker exposure, but these measurements have application for offsite exposure assessments as well. Continuous monitoring for air emissions at the fenceline, including dust, radon, and radon progeny, is an accepted practice by industry (see Chapter 8 for a discussion of monitoring best practices).

Processing Effects

Breaking the uranium ore into finer particles can occur as part of the mining or the processing. Processing will take place in a building, and significant controls can be in place to keep emissions to a minimum. Radioactive effluents that could be airborne include particles and gases. Control measures include enclosure of dusty operations, dust collection systems, dust suppression systems, spraying or wetting dust, ventilation systems specific to conveyor belts and other rock moving systems (see also Chapter 8 for best practices). Models can be used to predict off-site exposure to radon vented from the mining and processing operations.

Chemicals used as part of the processing operations, such as anhydrous ammonia or sulfuric acid used in leaching, could have significant off-site human health impacts under catastrophic accidental releases. Thus, facilities that store significant quantities (i.e., greater than 10,000 lbs) need to meet proper handling requirements, including safety equipment (e.g., devices preventing releases if hoses are severed, remotely operated shutoff valves) and training for employers and employees.[5] If more than 10,000 pounds of anhydrous ammonia are stored on-site, facilities are subject to additional regulatory controls (see Chapter 7).

Other chemicals that could be used in the processing operations include sulfuric acid, solvents such as high-purity kerosene, and peroxide. To minimize off-site impacts, air pollution controls need to be matched to the anticipated airborne effluents and appropriate scrubbing employed, with stack-based and off-site air quality monitoring to confirm proper equipment functioning (see Chapter 8).

Waste/Tailings Management Effects

Large amounts of rock are removed during the mining process that contain measurable quantities of uranium but are not economically viable for uranium production (also called protore). Therefore, large quantities of waste rock at a mining operation will emit radon and may generate wind-blown particulates if dust controls are not in place. Evaporation ponds and tailings impoundments are

[5] See http://www.osha.gov/dts/shib/shib120505.html.

another potential source of radon and airborne particulate radionuclides. Particular attention should be paid to dewatering activities of the waste or tailings because this may increase the rate of airborne contamination. Although protore and waste tailings may not contain enough uranium for processing to be cost-effective, there is still measureable radioactivity, which has off-site exposure potential.

If appropriately designed, capping of the waste storage pile can prevent airborne reentrainment of fine particles. Cap maintenance activities, however, will need to continue for thousands of years (potentially the responsibility of the U.S. Department of Energy Office of Legacy Management; see Chapter 7). Additionally, periodic inspection of the cap and repairs, as necessary, are essential to ensure that burrowing animals, erosion, or other weathering effects do not decrease the effectiveness of the cap in minimizing air pollution impacts.

General Mining-Related Concerns

During construction, exhaust from construction equipment, soil entrainment, and fugitive dusts will be generated, as at any construction site. Control measures would include dust suppression systems, spraying or wetting dust, and washing construction equipment before it leaves the site. Construction equipment and transport vehicles are powered by diesel engines, which generate diesel fumes.

Open-pit and subsurface mines have different air impacts. Open-pit mines generate dust directly to the air through blasting, loading into transport vehicles, and transport to the processing facility. Subsurface mines require ventilation systems to protect the workers, but vented dust will enter the ambient air. Air pollution controls, however, can be installed on the vents to decrease particulates.

ECOLOGICAL EFFECTS

Many of the ecological impacts of uranium mining and processing will be similar to other forms of hard-rock mining, in that both physical impacts and chemical impacts may occur. Physical impacts may include increased sediment loads and habitat disturbance, whereas chemical impacts may include emissions from diesel equipment or contaminated water from mine pits. The principal features that are specific to uranium mining will be the toxicity of radioactive materials and those materials co-occurring with uranium and the toxicity of chemicals specific to uranium processing. Therefore, this section begins with an overview of uranium-mining-specific effects, followed by a discussion of general mining effects.

Uranium Mining and Processing

Uranium mining and processing pose ecological risks beyond typical mining operations, particularly if the site is not managed using internationally accepted best practices. Past uranium mining activities in many parts of the world that were not in accord with modern best practices continue to require expensive remediation to clean up contaminated areas (see, e.g., Box 6.3). Modern mines treat the water from all mine operations, including the mine, processing facility, and tailings impoundment, prior to discharge and aim to control fugitive dust. Modern uranium processing operations are designed, constructed, and intended to be operated in a clean environment in which all materials are accounted. In such an ideal modern facility, fugitive emissions will be monitored and largely captured and not released into the environment. Under those circumstances, ecological risks from uranium mining and processing derive primarily from two categories: loading and transportation of the uranium product and chemicals used in the processing operations; and accidents or natural disasters, or management oversight failures that impair the normal operations of the processing, tailings management, or water treatment facilities.

Ecologically significant exposures primarily involve (1) spills, leaching, and surface runoff reaching streams and other aquatic environments; and (2) uptake of dissolved chemicals by plant roots. For these pathways, the most important radionuclides and chemicals are those that are water-soluble or are adsorbed to particles that can be suspended and transported by surface runoff and streamflows.

Radiological Effects

Ionizing radiation—specifically, α, β, and γ particles released through the decay of radionuclides—causes ecological effects via damage to biological tissues in exposed organisms. The effects of radiological exposure are related to the total amount of energy deposited, expressed in units termed Gray (Gy) per unit time (the radiological dose rate). This dose rate is the sum of doses from all sources, including natural background radiation, and includes both internal and external exposures. The International Atomic Energy Agency (IAEA, 1992) proposed guideline dose rates below which effects on plant and animal populations would be unlikely. These values are 400 μGy/hr for aquatic animals and terrestrial plants and 40 μGy/hr for terrestrial animals. These same values were used by the U.S. Department of Energy (USDOE, 2002) in its guidance on evaluating radiation doses to aquatic and terrestrial biota present at USDOE facilities. These limits are intended for application to long-term average exposures. Dose limits for episodic exposures to biota have not been promulgated, however, and any such limits would be expected to be higher than limits established for long-term exposures.

Internal doses result from uptake of radionuclides principally through inhalation and ingestion. Ingestion-related pathways can include consumption of

BOX 6.3
Uranium Site Cleanup to Mitigate Ecological Impacts in France

Uranium mining and associated operations in the vicinity of Limousin, France, began in 1947, with numerous orebodies being discovered and mined in peraluminous leucogranites. In 1993, the discovery that sediments and aquatic plants downstream from the Puy de l'Age mine were contaminated with radioactive waste raised concerns about public health and environmental hazards in the area and led to a sustainable redevelopment by the site owner, AREVA NC (formerly Cogema). By 1998, progress had been made in site cleanup and redevelopment, but several health and environmental concerns remained, including high contamination of river sediments and the presence of radioactive mud inside the mine basin. Nevertheless, in 1999 the local administration agreed with AREVA that the radiological situation at the Puy de l'Age mine was "normal" and that further water treatment and environmental monitoring was unnecessary. The last uranium mine in the area was closed in 2001.

In 2006, French authorities—including the Ministers of Ecology, Industry, and Health, as well as the President of the Nuclear Safety Authority—commissioned the Groupe d'Expertise Pluraliste sur les sites miniers d'uranium du Limousin (GEP; [Multidisciplinary Experts Group for the Uranium Mines of Limousin]) to evaluate recent progress made in the management of former uranium mining sites in France, both at the local level in Limousin as well as at the national level. The team conducted a thorough investigation of the risks and potential impacts to human health and the environment posed by these sites, examined the options for future site management and monitoring, and recommended best practices for improving management to reduce both current and long-term impacts. The GEP's final report was released in September 2010.

The GEP found that, although good progress has been made and should be continued in the management of former uranium mining sites, there were several key problem areas:

- Lack of an institutional body specifically responsible for directing activities at former uranium mining sites
- Lack of a timetable and specified process for transferring site-management responsibility from the company to public authorities
- Need for a systematization of site inventory and characterization tasks
- Insufficient research on and understanding of radioactive wastes on and around sites
- Limited range and scope of radiological impact evaluations
- Incompatibility of site monitoring devices with regulatory requirements
- Unreliability of existing safety systems in the long term
- Lack of information and public participation in sustainable site management

The GEP found that although current remediation measures have helped to control certain risks, there remain opportunities to increase the effectiveness of these measures in the near and long term. Their report called for the development of a strategy to integrate the technical, institutional, and social problems related to site management and the establishment of a program to address those problems. The report described a framework of recommendations based on the need for such a comprehensive program. As envisioned, the program would improve

research efforts on sites, reinforce information collection and sharing and dialogue among stakeholders, and guide a range of other activities undertaken by the site owner and other relevant local and national government organizations.

The GEP offered a variety of recommendations for the sustainable management of former uranium mining sites. The recommendations are divided into six major areas:

1. ***Institutional perspective and regulatory body***: The GEP proposed the establishment of an organization that is dedicated specifically to the affairs of former uranium mining sites. It also recommended the continued development of a legal framework that is adapted to current site-related risks.
2. ***Research efforts to improve knowledge***: The GEP recommended systematizing the characterization of sites to acquire better knowledge of potential sources of pollution. Current site characterization should be continued, but a strategic research program should also be developed to strengthen the understanding of key phenomena (hydrogeology, hydrochemistry, emission and transfer of radon, accumulation of radioactivity in the processing residues, etc.) as well as the knowledge regarding the toxicity of these substances.
3. ***Impact evaluations and public health policies***: The GEP found that impact evaluations to date have been mostly limited to public radiological exposures. It therefore recommended further development of the dosimetric evaluation method, which offers a more reliable estimation of the radiological doses from sites to the various exposure pathways. The GEP also emphasized the need for better evaluations of chemical impacts on humans, in addition to new evaluations of both the radiological and chemical impacts on ecosystems. This would require development of new monitoring tools and additional health monitoring in affected zones, accompanied by policies to protect the public against exposure to ionizing radiation.
4. ***Site surveillance systems***: The GEP found that devices deployed at certain sites are often incompatible with regulatory requirements. It recommended development of site surveillance systems that are better adapted to current knowledge of the potential risks and impacts related to site development. This should be accompanied by increased monitoring of the effects on local ecosystems, habitats, and the environment.
5. ***Robust safety systems to address long-term risks***: The GEP determined that existing safety systems on certain sites are unreliable in the long term, because they function on measures—such as land-use restrictions—that may degrade over time. Stakeholders should consider technical and social issues, in addition to a broad range of scenarios, to reinforce the long-term robustness of existing safety systems. This would involve preparing and formalizing a decision-making process to implement long-term management options.
6. ***Information and participation in sustainable site management***: The GEP found that current efforts to address the lack of information and participation in sustainable site management are inadequate. It recommended expanding efforts to collect site information and share it with the local population. Local-scale site management will require additional support from the local Commissions of Information and the creation of feedback mechanisms around the sites. The GEP emphasized the importance of maintaining a dialogue between the local and national levels to reinforce information sharing and follow up on actions.

SOURCE: GEP (2010).

contaminated water or food, and incidental ingestion of soil or sediment that contain radionuclides. External doses result from decay of radionuclides present in environmental media in the immediate vicinity of an organism. The amount of external radiation absorbed by an organism from a particular decay event depends on the type of radiation released (only β particles and γ rays can penetrate the skins or external membranes of organisms), the distance between the organism and the source, and the size and external geometry of the organism. An aquatic plant will receive a different external dose from the same radiation source than will an invertebrate feeding on the plant or a fish that consumes the invertebrate.

Although these exposure pathways are complex, radiation biologists have developed models to quantify them. The USDOE (2002) guidance document contains models for quantifying total dose rates for aquatic animals, riparian zone animals, terrestrial animals, and terrestrial plants. The models are radionuclide-specific, and include models for ^{238}U and daughter products, including all of the decay chains discussed in Chapter 5 (see Figure 5-1). The guidance provides methods for using these models to calculate biota concentration guides (BCGs), which are concentrations of specific nuclides in environmental media that would produce a dose exactly equal to the recommended dose limit, considering all environmental pathways and both external and internal exposures. These BCGs can be used to identify thresholds of concern in environmental media.

Chemical Toxicity

Uranium toxicity. Under oxidizing conditions, uranium in aquatic environments is generally present in the hexavalent state (U^{6+}), although the aqueous species will depend on a variety of factors, including pH, alkalinity, and complexing agents, such as dissolved organic matter or phosphate). The speciation and complexation affect the toxicity of uranium in the environment. The most bioavailable and toxic form present under typical environmental conditions is the divalent uranyl (UO_2^{2+}) ion (Cheng et al., 2010). A wide variety of uranium toxicity studies have been performed using terrestrial plants, soil invertebrates, soil microorganisms, aquatic invertebrates, fish, and mammals. Uranium toxicity to fish is hardness-dependent (with toxicity being inversely related to hardness), although hardness does not affect the toxicity of uranium to other aquatic organisms. Sheppard et al. (2005) reviewed the toxicity literature for uranium and derived the predicted no-effect concentrations (PNECs), which are concentrations of uranium in water or soil below which no adverse effects on exposed organisms are anticipated to occur:

- Terrestrial plants, 250 mg U/kg (dry soil)
- Other soil biota, 100 mg U/kg (dry soil)
- Freshwater plants, 0.005 mg U/L
- Freshwater invertebrates, 0.005 mg U/L
- Freshwater benthos, 100 mg U/kg (dry sediment)

- Freshwater fish in very soft water (hardness of <10 mg $CaCO_3$/L), 0.4 mg U/L
- Freshwater fish in soft water (hardness of 10-100 mg $CaCO_3$/L), 2.8 mg U/L
- Freshwater fish in hard water (hardness of >100 mg $CaCO_3$/L), 26 mg U/L

Considering all types of aquatic organisms, Mathews et al. (2009) calculated a PNEC of 3.2 µg/L (0.0032 mg/L) for freshwater ecosystems.[6] The various PNEC values calculated for uranium indicate that uranium is similar in toxicity to metals such as copper and cadmium.

Some authors have suggested that chemical toxicity of uranium is usually more important than radiological toxicity, but Mathews et al. (2009) found that this is not the case for all of the exposure scenarios evaluated. Mathews et al. (2009) recommended that ecological risk assessments for uranium should consider both chemical toxicity and radiological toxicity, including the radioactivity associated with the decay of uranium daughter products.

Toxicity of other radionuclides. Chemical toxicity of uranium daughter products has not been considered a significant issue in uranium mining or processing. Thorium is of potential interest because it may occur in higher concentrations than uranium in typical uranium ores and typically occurs in higher concentrations in the waste rock and tailings. Two published studies (Correa et al., 2008; Kochhann et al., 2009) investigated the uptake and toxicity of a soluble form of thorium (thorium nitrate) to the silver catfish (*Rhamdia quelen*). Both studies demonstrated the uptake of thorium by fish tissue, especially the gill, and skin, and also demonstrated biochemical and histological changes resulting from thorium exposure. However, no effects on growth or survival (Correa et al., 2008), which are more ecologically relevant effects, were found, and the chemical form of thorium used in the experiments is not a form in which thorium would typically be found in the environment. Carvalho et al. (2007) found elevated concentrations of uranium, radium, and polonium in fish collected from rivers affected by historical mining operations in Portugal. Thorium was retained in riverbed sediments and was detected only at very low levels in fish. Hence, information currently available suggests that no radionuclide other than uranium is of environmental concern due to chemical toxicity.

Toxicity of nonradiological chemicals. Toxicity information for those chemicals and other water quality characteristics associated with uranium mining and processing that are most likely to be of greatest ecological significance are briefly summarized in Boxes 6.4 and 6.5. These include substances potentially present in mine water or treated effluent (e.g., dissolved salts), substances potentially

[6]For comparison, reported surface water concentrations of uranium downstream of the Rum Jungle mine in Australia, which operated in the 1950s and 1960s with little concern for environmental impacts, ranged from 6 to 63 µg/L (mean of 33 µg/L) in 1992-1993 (Mudd and Patterson, 2010).

leached from waste rock or tailings (e.g., selenium, vanadium, nickel, copper, aluminum, iron; see Box 6.4), and chemicals potentially released during spills (e.g., sulfuric acid, sodium hydroxide, carbonate, ammonia, decanol, kerosene; see Box 6.5).

Ecological Monitoring at Uranium Mine Sites

The committee was able to locate ecological monitoring data for only a few uranium mining sites, and these data show that adverse impacts sometimes occur, but do not always occur when facilities are properly managed. At the Ranger Mine in Australia, biological monitoring has revealed no significant changes to aquatic biota or fish communities downstream from the mine, and no significant bioaccumulation of mining-related contaminants in fish or shellfish (Supervising Scientist, 2008). However, biological monitoring in Island Lake downstream from the Cluff Lake mining and processing operation in Canada showed shifts in benthic invertebrate communities to more metal-tolerant species. Moreover, bioaccumulation of uranium, selenium, and radium was observed in fish tissues (CNSC, 2003).

Selenium in particular has been identified as a contaminant of concern at two modern uranium mining and processing operations in Saskatchewan—Key Lake (Wiramanaden et al., 2010) and McClean Lake (Muscatello and Janz, 2009a). At both of these sites, selenium was found to accumulate in the tissues of aquatic biota, even though concentrations of dissolved selenium in the water column were low. The environmental transformations and transfer pathways responsible for this accumulation appear to be quite complex. Wiramanaden et al. (2010) found that selenium accumulated in benthic invertebrates in Fox Lake, downstream from the treated effluent discharge from the Key Lake Mill. The authors concluded that inorganic selenium was being adsorbed by phytoplankton in Fox Lake, settling to the bottom sediments, being converted to organic forms by microorganisms present in the sediment, and being transferred to benthic invertebrates that feed on organic detritus present in the sediment. The authors also found that the rate at which selenium is removed from the water column and transferred to sediment and biota is influenced by both water chemistry and sediment characteristics, especially sediment total organic carbon. Similarly, Muscatello and Janz (2009a) found selenium accumulation in phytoplankton, benthic invertebrates, and fish in Vulture Lake, which receives treated effluent from the McClean Lake mine site. The highest concentrations were observed in fish, although Muscatello and Janz (2009b) found no overt effects of selenium exposures on adult spawning northern pike and white sucker fish or on the eggs and larvae compared with those in a nearby uncontaminated lake.

As discussed previously in this chapter, acidic surface water and groundwater have been found at uranium sites in Brazil, Portugal, Australia, and Canada. The chemical and biological processes responsible for this acidification, and associated mobilization of toxic metals such as copper and zinc, are the same

BOX 6.4
Ecological Effects of Key Substances Potentially Present in Mine or Tailings Discharge

This box discusses the ecological effects of key constituents with significant ecotoxicity that are likely to be present at some level in uranium mine or tailings discharge. The concentration and exposures ultimately affect the extent of ecological effects. Acid mine drainage conditions can lead to particularly elevated concentrations of these constituents.

Many metals and metalloids are substantially more toxic to aquatic biota than to humans. Table 6.1 compares, for those constituents for which water quality criteria have been promulgated by the Virginia Department of Environmental Quality, the criteria for aquatic life protection and the criteria for drinking water. The likelihood of environmental risk from these various constituents depends on their concentration in the orebody and the host rock. For example, arsenic and selenium have been found associated with uranium at ore deposits in Canada, but they are not present in significant concentrations in the Coles Hill, Virginia, deposit. Nevertheless, arsenic and selenium may be present in other uranium ore deposits in Virginia.

Dissolved salts. High concentrations of dissolved salts can be toxic to freshwater aquatic organisms (e.g., Sarma et al., 2005). Both mine water and treated processing effluents often contain high concentrations of salts. Salinity is frequently measured in terms of electrical conductivity, and the appropriate inland freshwater conductivity has been determined to lie between 150 and 500 μsiemens/cm.

Acidity. Streams affected by acid mine drainage have degraded benthic invertebrate communities and much lower densities of fish than do streams that have not been affected (Earle and Callaghan, 1998). It is difficult to identify the specific causes of these effects because the low pH and the high concentrations of metals present at low pH are toxic to aquatic biota. Neutralization of acidic waters through mixing with unpolluted ambient water can result in precipitation of iron, aluminum, and other metals. These precipitates coat the substrate and cause additional biological degradation.

Selenium. Selenium is a potentially hazardous substance that interacts with different compounds and can behave differently depending on these interactions and environmental conditions. Selenium can accumulate and biomagnify, and exposure to high concentrations can cause reproductive failure and birth defects (USEPA, 2004; Lenntech, 2011b). The USEPA (2004) has published a draft water quality criterion of 7.91 μg/g dry weight expressed as a concentration in fish tissue.

Copper. Copper can be toxic to both aquatic biota and terrestrial plants. Reduced growth or photosynthesis in algae and teratogenic effects in sensitive species or fish amphibians have been seen in environments with copper concentrations as low as 5-10 ppb (Maag et al., 2000). The presence of copper has been shown to reduce macroinvertebrate survival as well as contribute to adverse structural and functional effects of fish nervous systems. Exposure to high con-

continued

BOX 6.4 Continued

centrations of copper can also cause gill tissue damage and even lead to death (USEPA, 2007).

Aluminum. Aluminum can accumulate in plants, affecting enzyme systems important for the uptake of nutrients. In addition, aluminum contamination can cause adverse health impacts to animals that consume these plants. In aquatic environments, aluminum ions react with proteins in the gills of fish and the embryos of frogs, resulting in impaired gas exchange, which can be particularly severe in low-pH waters (Dietrich and Schlatter, 1989). Aluminum contamination can also cause adverse effects on birds and other animals that eat contaminated fish and insects, such as eggshell thinning and low birth weights of chicks (Lenntech, 2011a).

Vanadium. Vanadium bioaccumulation has resulted in pervasive elevated concentrations in a variety of plant and animal species. Ecological exposures may lead to neurological and reproduction complications, breathing disorders, and liver and kidney problems (Lenntech, 2011b).

Iron. Ferric hydroxide and iron–organic matter precipitates in surface waters disturb the metabolism and osmoregulation of organisms. In addition, these precipitates change the structure and quality of benthic habitats and food resources, which decrease the species diversity and abundance. Ferric iron also lowers the pH when it hydrolizes in water (Vuori, 1995).

TABLE 6.1 Comparison Between Virginia DEQ Water Quality Criteria for Aquatic Life Protection and for Public Drinking Water

	Aquatic Life (µg/L)				
	Freshwater		Saltwater		
Chemical	Acute	Chronic	Acute	Chronic	Public Water Supply(µg/L)
Aluminum[a]	750	87	—	—	—
Arsenic	340	150	69	36	10
Cadmium	3.9	1.1	40	8.8	5
Copper	13	9.0	9.3	6.0	1,300
Lead	120	14	—	—	15
Nickel	180	20	—	—	610
Selenium	20	5.0	—	—	170
Vanadium	280	19	90	81	—
Zinc	120	120	—	—	7,400

[a]Applicable at pH 6.5-9.0.
NOTE: Dashes indicate that no criteria have been established.
SOURCE: Virginia Department of Environmental Quality Regulation 9VAC-260-140: Criteria for Surface Water.

BOX 6.5
Ecological Effects Possible from Chemical Spills

The following chemicals used in uranium processing have the potential to affect ecological health if significant quantities are spilled:

Sulfuric acid. Sulfuric acid poses moderate acute and chronic toxicity to aquatic life. Exposure may cause superficial burns and lesions on animals. Although small quantities may be neutralized, larger amounts may affect water pH levels, causing acidic conditions. Acidic conditions may promote leaching of other compounds, such as aluminum and iron, from soils (DSEWPC, 2011).

Sodium hydroxide. Although sodium hydroxide is not directly toxic to aquatic life, large enough amounts may cause water pH to rise above the tolerance limits of some freshwater aquatic species (California EPA, 2003).

Carbonate and bicarbonate. Carbonate and bicarbonate are not inherently toxic compounds, but elevated levels may cause indirect negative effects on an aquatic system by raising water pH (Lottermoser, 2010).

Ammonia. At a low pH and temperature, ammonia combines with water to produce ammonium and a hydroxide ion, which is nontoxic. Above pH 9, un-ionized ammonia is predominant and can readily cross cell membranes, allowing ammonia to accumulate in organisms. Exposure to ammonia at high levels may cause increased respiratory activity and increased heart rate in fish. In addition, exposure can lead to reduction in hatching success, reduced growth and morphological development, and injury to gill tissue, liver, and kidneys. Impacts such as hyperplasia of the gill lining in salmon fingerlings and bacterial gill disease have been seen at even slightly increased levels of ammonia (0.002 mg/L for 6 weeks). Various fish species can die at concentrations of 0.2 to 2.9 mg/L, with trout being the most susceptible and carp the least (CSREES NCWQP, 1976).

Decanol. Decanol biodegrades readily and is expected to adsorb to suspended solids in water and sediment. There is a moderate potential for decanol to bioconcentrate in aquatic organisms. Decanol poses a slight to moderate toxicity to freshwater fish and a moderate toxicity to saltwater fish.

Kerosene. Kerosene spills could result in potential acute toxicity to some forms of aquatic life. The lighter, more volatile compounds of kerosene, such as benzene, toluene, and xylene, could cause long-term contamination hazards to the groundwater. The polycyclic aromatic hydrocarbon compounds in kerosene may be translocated and accumulated in plants. Chronic effects of exposure to some constituents in kerosene include changes in liver; harmful effects on kidneys, heart, lungs, and nervous system; increased rates of cancer; and immunological, reproductive, fetotoxic, and genotoxic effects (Irwin et al., 1997).

processes responsible for acid mine drainage from coal mines in the eastern United States. Biological data are not available for most of these sites. However, information on the effects of acid drainage on stream fish communities and on the recovery of fish communities following remediation is available from studies performed at the Rum Jungle uranium mine site in Australia. The Rum Jungle

mine released untreated mine waters into the Finniss River during the 1950s and 1960s. Biological studies performed in the 1970s showed that during low flow periods the abundance and diversity of fish and decapod crustaceans in the Finniss River immediately downstream from the discharge were substantially reduced. Significant fish kills were observed when low flows in the Finniss River coincided with moderate inflows from the mine site (Jeffree and Williams, 1980). Elevated concentrations of cobalt, nickel, copper, zinc, and manganese occurred as far as 30 km downstream from the mine site. Fish kills were associated with pulses of highly contaminated water released during the onset of the rainy season. Following remedial actions performed in the 1980s, both the average metal concentrations and the magnitudes of seasonal pulses were greatly reduced. A fish community study performed during the 1990s (Jeffree et al., 2001) showed that the fish community present in the Finniss River immediately downstream from the inflow from the mine was similar to the community present at unaffected sites. No fish kills were observed. The adverse effects observed downstream from the mining and processing operations described above have been attributed to chemical toxicity, rather than to radiological exposures. There is no evidence that radiological dose limits for aquatic or terrestrial biota were exceeded in any of these cases.

General Mining-Related Ecological Effects

Many of the sources of stress to ecological systems are not specific to uranium mining, but may be associated with any mining activities or substantial ground-clearing development. The effects of mining can be divided into on-site ecological effects from the significant disruption of the land surface in the mined area and off-site effects.

On-site Effects

The principal ecological impacts during the construction phase derive from the ground disturbance associated with excavation and construction, operational emissions from construction equipment, and increased human presence in the area. The process of constructing buildings, roads, and the site preparation will eliminate the soil habitat on the immediate footprint of all permanent site features. This loss will have long-term ecological effects in cases where woodlands or forests are removed and not restored, although it may be possible to restore grasslands following site closure. Revegetation with native plants, however, can be a challenge because of changes in soil quality and pressures from invasive species. A significant indirect impact on habitat will be the consequences of loss of shade trees. Shade trees provide both habitat for various species as well as modulation of temperature, wind, and rainfall. Shade trees also lower air and surface soil temperatures and water temperatures of adjacent streams.

Off-site Effects

Sediment. Construction and ground-disturbing activities often cause soil erosion and increased stormwater runoff. State and local regulations and ordinances require erosion and sediment control measures such as retention ponds, straw bales, and earthen berms, termed best management practices. These practices seldom, if ever, prevent erosion and sedimentation entirely, although the problem may be mitigated. Excess sediment is recognized as a principal cause of impairment to freshwater streams and creeks nationwide and throughout Virginia (Suren, 2000; USEPA, 2010). Replacing sand or gravel surfaces with silt and fine sediment can make the habitat unsuitable for indigenous flora and fauna. Sediment also can clog the gills of many aquatic animals, leading to impaired growth and physiological function and sometimes death. Excess sediment is also a leading cause of water quality impairment in the Chesapeake Bay and coastal North Carolina embayments into which most Virginia surface waters drain. In these coastal waters, waterborne sediment blocks sunlight and coats plant surfaces, both of which limit the ability of underwater grasses to photosynthesize, reducing growth and causing mortality. These underwater grass beds are an important habitat that has been reduced over time and are the target of significant restoration efforts (Batuik et al., 2000).

Major mining operations could require increased transportation infrastructure in Virginia, meaning more roads or improved roadways. Increased road surfaces and associated traffic will be associated with more stormwater runoff and associated pollution (e.g., nitrogen, sediment, organic chemicals, heavy metals). New roadways and railways that disturb forestland may have the consequence of bisecting and disturbing habitat.

Other chemicals. Sediment and water discharged off-site could contain a wide variety of ecologically hazardous materials, depending on the chemical composition of the ores being mined. Elevated concentrations of salts and other dissolved materials (total dissolved solids or TDS) caused by mining and processing activities can affect the health of freshwater biota. Depending on water chemistry (especially pH), a variety of metals and metalloids, including copper, iron, aluminum, vanadium, and selenium can be released in high quantities. Releases of water containing high concentrations of dissolved metals are typically associated with acid mine drainage, as discussed previously in this chapter. Discussion on specific ecological effects of these constituents is provided in Box 6.3.

ENVIRONMENTAL MONITORING

A well-designed and executed environmental monitoring plan is an essential component of any uranium mining and processing operation. In this section, the goals and key components of a monitoring program are discussed. Additionally,

the section discusses ways to engage stakeholders in the development and implementation of the monitoring plan.

Monitoring Goals

A monitoring strategy will need clear goals and a feasible strategy by which those goals can be achieved. The major purposes of an environmental monitoring and assessment program include:

- ***Determining and demonstrating compliance.*** A monitoring program is frequently used to assess whether the facility is in compliance with environmental and worker-safety regulations. An equally important aspect is assessing the attainment of best-practice discharge targets, which may be significantly lower than regulatory limits.
- ***Triggering corrective actions***. Monitoring data can guide facility operators to implement corrective actions (e.g., improved engineering controls or management procedures) when predetermined trigger points are exceeded. A well-constructed monitoring and assessment plan can enable early detection of system failures (whether caused by natural events, human error, or criminal acts), thereby preventing more widespread contamination.
- ***Fostering transparency***. Providing timely and readily accessible information to stakeholders about measured environmental contaminant levels and doses to persons can provide assurances to the community that they are not subject to adverse impacts that are unseen and unmeasured. Thus, monitoring can foster a broadly informed local community and bridge the gap of mistrust of the regulatory process. Transparent monitoring also ensures that personal and community interests are protected during the facility operation and after closure.
- ***Enhancing site-specific understanding***. Knowledge gained through baseline and operational monitoring can be used to improve the understanding of site-specific hydrogeology and contaminant transport pathways. This knowledge can be used to refine site-specific conceptual models or validate and refine numerical models of the site, such as hydrologic, contaminant transport, and air dispersion models. Information gained from monitoring can also provide the basis for evaluating the monitoring plan itself and making improvements as needed.

Additionally, facilities may use other on-site monitoring to aid in documentation of material control and security, through material balances (see also NCRP, 2011)

In the long term, robust monitoring should also lead to better-informed operational, management, public policy, and regulatory decisions. One of the keys to any environmental and public health protection program is an environmental monitoring strategy that is designed to inform these decisions. This strategy would include (1) determinations of the types environmental measurements (e.g.,

biological, water, air, soil), their spatial distribution, and their temporal frequency necessary to adequately inform regulatory and operational decision making and address community concerns; (2) policy and regulatory decisions on how change in the environment will be detected, measured, and qualified; and (3) how much change from the baseline is of regulatory and operational significance.

Key Aspects of Monitoring

Monitoring occurs during all phases associated with uranium mining. A well-designed monitoring program is based on a set of agreed-upon goals, as discussed in the previous section, rather than a set of proscribed practices (e.g., number, location, and depth of wells). This monitoring program would begin well in advance of site operations (i.e., baseline monitoring) and continue during operations, reclamation, and well after closure and decommissioning.

Baseline Monitoring

Comprehensive baseline surveys of environmental characteristics are conducted prior to the start of mining and processing operations to provide an understanding of premining and processing conditions. These data are essential for comparing environmental conditions after the onset of construction and operations against background contaminant levels. Baseline data will also provide a basis for returning the land to unrestricted use after the operations cease. Finally, baseline data will be useful during emergency response for surveying contamination in the event of an unplanned release.

Baseline characterization includes, at minimum, chemical, physical, and radioactive elements of the water, air, and soil; biological indices (e.g. benthic index); habitat characterization; and identification of species or communities of special interest that could be affected by construction or facility operation. The spatial extent of baseline monitoring would need to encompass the mine site and offsite areas with potential for environmental impacts, with particular attention paid to downgradient groundwater resources and downstream water resources that could be affected by water pollutants released from the mining operations. The length and frequency of baseline monitoring would need to be sufficient to capture the natural inter- and intraannual variability. The measurements of radionuclides and other chemicals of concern in environmental media (i.e., air, water, vegetation, and representative fauna) should be obtained for a minimum of 1 full year, but ideally would take place over several years. The selection of measurement methods with adequate sensitivity is critical.

Ideally, a group of stakeholders would be assembled to design the baseline monitoring program. This could include managers of the facility, support staff, technical experts, regulatory officials, potentially exposed residents nearby, and public interest groups. This core group should then develop a mechanism for

soliciting the input of a wider and more diverse group including chemists, engineers, dose modelers, statisticians, technical project managers, community representatives, immediate neighbors, data users, public officials, and decision makers. A detailed description of the process is outlined in NCRP (2011) for reference. Based on the use of the data, the monitoring program can be designed to include the frequency, sample size, location, and parameters that are of interest.

Baseline data collection would represent one aspect of a more comprehensive site characterization effort, from which site-specific conceptual and numerical models would be generated to integrate the data collected into a system-level understanding. Conceptual models are diagrams or narrative descriptions that synthesize complex data and concepts regarding potential exposures and site-specific transport processes into an accessible format that offer an important tool for communicating with public stakeholders, regulators, and risk assessors (Suter, 1999; Cygan et al., 2006). Numerical models are mathematical tools that use equations to describe the relationships among system components and can be used to make quantitative predictions. A model (or models) developed for a uranium mining/processing project should include all significant environmental pathways linking potential sources of radionuclides and nonradiological contaminants to human and nonhuman receptors. Key pathways would likely include surface water, groundwater, and atmospheric emissions, as well as direct gamma-ray exposure. These tools would also be essential to the development of contamination response plans.

Operational Monitoring

Like the baseline data collection, operational monitoring programs (i.e., frequency, sample size, location, and parameters) ideally would be developed with substantial stakeholder input, so that the monitoring data can be used to inform decision making among various stakeholders. An operational monitoring strategy would likely continue the baseline monitoring, perhaps with altered temporal sampling as appropriate to address the decision needs of regulators, facility managers, and the public. This monitoring would be used to determine (1) failures of engineered control strategies, (2) actual or potential adverse impacts upon public health and/or the environment, or (3) breaches in regulatory requirements. The optimum time interval between sampling events would depend on the potential hazards and the remedial action options (including natural attenuation), considering contamination scenarios that could occur over the time period between sampling events.

Environmental radiation monitoring for uranium mines (whether open-pit or underground) would include three levels of monitoring. Real-time radiation monitoring (e.g., ion chambers and gamma-ray spectrometers) can provide instantaneous readings that would be relevant in an emergency. Integrated monitors assess radiation exposure over a period of time (e.g., 2 weeks), which provides a

greater sensitivity but no instantaneous readings. For example, thermoluminescent detectors could be installed in concentric rings around the facility to detect high levels of airborne radioactivity. Finally, a program of measurement of radiation in biota is needed to determine whether the bioaccumulation of radionuclides is occurring within the food chain (NCRP, 2011).

Regular assessments of all monitoring data, including trend analyses, are important to test the accuracy of predictions and, if necessary, to modify the mitigation and remediation practices. The determination that contamination has occurred is based on comparison of data from upgradient and downgradient wells against a comprehensive preoperation baseline. This, in conjunction with a robust statistical analysis plan, will help to determine a true contamination event from a false positive or an observation within natural variability. True exceedances would trigger the need for corrective actions. A clear process is needed for reviewing monitoring data, including an annual independent review of monitoring data, and adjudicating data discrepancies. The operational monitoring plan is best developed and updated in close cooperation with facility design and operations staff to adapt to changes in operations (e.g., relocated facilities, changes to process chemicals used).

Operational monitoring strategies need to be based upon the best available understanding of the regional hydrogeology, atmospheric conditions, and biosphere. Monitoring data and new science may improve the existing understanding of potential contaminant release or transport pathways. Thus, although initial monitoring objectives are identified for each of the chosen environmental compartments, the monitoring strategy needs to be adaptable to respond to new knowledge. To ensure that the monitoring plan and site conceptual and numerical models are appropriate and reflect the latest scientific understanding, the monitoring plan and site models should be reviewed annually by an independent group of qualified experts. Ideally, such a review panel would include experts nominated by public stakeholders and regulators. The results of the monitoring and model review, including recommendations for improvements, would be released to the public and submitted to the relevant authorities in a timely fashion.

Decommissioning Monitoring

The purpose of environmental monitoring during decommissioning is to evaluate the potential doses to members of the general public and demonstrate compliance with regulatory requirements because activities associated with site remediation can pose different environmental concerns than those encountered during operations. For instance, a uranium mill tailings impoundment that is partially covered with water during facility operation may be dewatered and dried prior to covering. This could increase the potential for radon or particulate emissions. Therefore the environmental monitoring program in place during operations would not be sufficient during decommissioning to account for this

situation. The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides the methodology for developing a site decommissioning survey (USEPA et al., 2000). The intended use of the manual is to demonstrate that the site is sufficiently remediated to meet the decommissioning criteria. A separate document, the Multi-Agency Radiological Survey and Assessment of Materials and Equipment (MARSAME) Manual[7] has been prepared to provide guidance for documentation of monitoring required before release of expensive heavy equipment (i.e., bulldozers) or transport of waste to off-site locations.

Data Quality

Guidance on data quality objectives for monitoring data are described in the Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP) Manual (USEPA et al., 2004). The MARLAP Manual was prepared to address the need for a nationally consistent approach to producing radioanalytical laboratory data that meet a project's or program's data requirements and is considered to be the definitive guide for sampling and analysis. Data quality objectives are discussed extensively in the manual detailing the laboratory procedures for analyzing samples.

The decision about which devices to deploy, where they would be located, and how frequently samples would be taken, would be dictated by the objectives of the monitoring strategy, including the precision, accuracy, and uncertainty that are determined to be acceptable. The quality assurance project plan is the place where all of these decisions are documented so that the objectives are clear to the staff executing the monitoring plan, as well as regulatory officials and the public.

Finally, a data management plan will need to be developed to (1) ensure that all monitoring data and associated metadata are archived and (2) facilitate easy retrieval of the data and metadata by interested parties (public, regulators). A publicly accessible scientific data clearinghouse would provide transparency and common ground for public policy and regulatory debate.

Multistakeholder Environmental Monitoring Infrastructure Approach

A multistakeholder environmental monitoring strategy is an effective approach to address multiple concerns in crafting the monitoring program and to maintain trust among a diversity of stakeholders. The "first line" of monitoring could involve direct efforts by the facility operator or by monitoring performed under contract to the owner by local research institutions or private consultants. This first line of monitoring could also include separate monitoring efforts operated solely by state or federal regulatory authorities. A second line of monitoring could be managed by a local community group through a community technical assistance grant (TAG) with funds from the facility operator. Through this effort,

[7] http://www.epa.gov/rpdweb00/marssim/marsame.html.

community members, with assistance from independent scientific experts, would identify monitoring needs of particular importance and contract for sampling and analysis by infrastructure different from that of the mine operator. A third line of monitoring could involve local authorities such as cities, municipal water purveyors, or local air pollution control districts, who could identify monitoring strategies focused on their specific jurisdictions. Funding for this third line could be derived from the "mill tax" on per kilowatt of energy derived from the mined uranium. Like that for the community TAG effort, analysis of these samples would be done by laboratory entities different from that of the mine operator. All monitoring described above would need to be conducted according to quality assurance/quality control specifications determined by the relevant regulator.

FINDINGS AND KEY CONCEPTS

The committee recognizes that mining, processing, and reclamation, by nature, can cause long-term impacts to habitats (on the order of decades to centuries), hydrological alterations, and adverse changes to water quality. Virginia has extensive experience with mining and its impacts, and thus the primary focus of this chapter is on the specific environment impacts of uranium mining. The committee arrived at the following findings regarding the environmental impacts that might occur if the moratorium on uranium mining in Virginia were to be removed:

- ***Uranium mining, processing, and reclamation in Virginia have the potential to affect surface water quality and quantity, groundwater quality and quantity, soils, air quality, and biota. The impacts of these activities in Virginia would depend on site-specific conditions, the rigor of the monitoring program established to provide early warning of contaminant migration, and the efforts to mitigate and control potential impacts.*** A substantial literature exists that describes the environmental hazards resulting from past uranium mining that was largely conducted using standards of practice generally not acceptable today. Documented impacts include water quality effects (e.g., elevated concentrations of trace metals, arsenic, and uranium) caused by acid mine drainage or oxidation of groundwater, localized reduction of groundwater levels, off-site dust transport, and impaired populations of aquatic and terrestrial biota. If uranium mining, processing, and reclamation are designed, constructed, operated, and monitored according to modern international best practices (see Chapter 8), the committee anticipates that the near- to moderate-term environmental effects specific to uranium mining and processing should be substantially reduced. Nevertheless, studies at relatively modern uranium mines have documented acid mine drainage associated with waste rock piles and effects on aquatic biota from selenium and metals derived from treated effluent.
- ***Tailings disposal sites represent potential sources of contamination for thousands of years, and the long-term risks remain poorly defined.*** In recent

years, significant improvements have been made to tailings management practices to isolate mine waste from the environment, and belowgrade disposal practices have been developed specifically to address concerns regarding tailings dam failures. However, the short period of monitoring data at these sites provides insufficient information from which the committee can judge the long-term (200- to 1,000-year) effectiveness of modern uranium tailings management facilities in preventing groundwater and surface water contamination. The potential long-term environmental effects posed by uranium mining and processing waste (e.g., widespread groundwater and surface water contamination) are likely to be more than trivial if waste management facilities fail to perform as designed. Major failures would necessitate aggressive remediation strategies and possibly long-term active site management to limit off-site migration and restore the affected area.

- ***Significant potential environmental risks are associated with extreme natural events and failures in management practices.*** Extreme natural events (e.g., hurricanes, earthquakes, intense rainfall events, drought) have the potential to lead to the release of contaminants if facilities are not designed and constructed to withstand such events, or fail to perform as designed. The failure of a tailings facility is one example of a design failure that could have widespread human health and environmental effects. Extreme weather events are not rare in Virginia, and need to be carefully and appropriately considered in facility design, management, and maintenance. Management issues or human error, as well as criminal acts such as intentional release, could lead to large-scale environmental contamination by hazardous materials or radionuclides used or stored on-site. The empowerment of all regulatory and mine- and processing-site staff to report and address deficiencies can reduce such occurrences or minimize their impacts. Thoughtful environmental monitoring design can also lead to early detection of contamination caused by management failures, thereby lessening the extent of any offsite remediation that might be required. Until comprehensive site-specific risk and vulnerability assessments are conducted, including accident and failure analyses, the short-term risks associated with natural disasters, accidents, and spills remain poorly defined.
- ***Models and comprehensive site characterization are important for estimating the potential environmental effects associated with a specific uranium mine and processing facility.*** A thorough site characterization, supplemented by air quality and hydrological modeling, is essential for estimating the potential environmental impacts of uranium mining and processing under site-specific conditions and mitigation practices. Ongoing water and air quality monitoring are necessary to confirm model predictions and provide the basis for updating and revising these models as additional site-specific data become available.

7

Regulation and Oversight of Uranium Mining, Processing, Reclamation, and Long-Term Stewardship

Key Points

- The activities involved in uranium mining, processing, reclamation, and long-term stewardship are subject to a variety of federal and state laws that are the responsibility of numerous federal and state agencies.
- Because the Commonwealth of Virginia enacted a moratorium on uranium mining in 1982, the state has essentially no experience regulating uranium mining and there is no existing regulatory infrastructure specifically for uranium mining. The state does have programs that regulate hard-rock mining and coal mining.
- There is no federal law that specifically applies to uranium mining on non-federally owned lands; state laws and regulations have jurisdiction over these mining activities. Federal and state worker protection laws, and federal and state environmental laws variously apply to occupational safety and health, and air, water, and land pollution resulting from mining activities.
- At present, there are gaps in legal and regulatory coverage for activities involved in uranium mining, processing, reclamation, and long-term stewardship. Some of these gaps have resulted from the moratorium on uranium mining that Virginia has in place;

others are gaps in current laws or regulations, or in the way that they are applied. Although there are several options for addressing these gaps, the committee notes that Canada and the state of Colorado have enacted laws and promulgated regulations based on best practices that require modern mining and processing methods, and empower regulatory agencies with strong information-gathering, enforcement, and inspection authorities. In addition, best practice would be for state agencies, with public stakeholder involvement, to encourage the owner/operator of a facility to go beyond the regulations to adopt international industry standards if they are more rigorous than the existing regulations.

- The U.S. federal government has only limited recent experience regulating conventional[1] uranium processing and reclamation of uranium mining and processing facilities. Because almost all uranium mining and processing to date has taken place in parts of the United States that have a negative water balance (i.e., dry climates with low rainfall), federal agencies have limited experience applying laws and regulations in positive water balance (i.e., wet climates with medium to high rainfall) situations. The U.S. federal government has considerable experience attempting to remediate contamination due to past, inappropriate practices at closed or abandoned sites.
- Under the current regulatory structure, opportunities for meaningful public involvement are fragmented and limited.

This chapter discusses the laws, regulations, and policies—and the relevant federal agencies—that are applicable to uranium mining, processing, reclamation, and long-term stewardship. Because of Virginia's moratorium on uranium mining, Virginia state agencies have not been permitted to develop a modern state-specific regulatory environment. However, to the extent possible, the Virginia agencies that might be involved in regulating mining, processing, and reclamation if the moratorium were to be lifted are identified. For purposes of comparison, brief information on the regulatory environment in Canada and Colorado are included (Boxes 7.1, 7.2). These two examples are noted here because they are situations where there has been ongoing and recent development

[1]Conventional mining and processing includes surface or open-pit mining, or some combination of the two, and their associated processing plants, but excludes ISL/ISR uranium recovery.

of laws and regulations applicable to uranium mining, processing, reclamation, and long-term stewardship. While the committee considers that neither constitutes an ideal model regulatory environment, both illustrate the ongoing evolution of a regulatory environment that either recognizes or drives the continuing development of best practices in the industry.

The committee's statement of task (Box 1.1) requires that it "review the state and federal regulatory framework for uranium mining, milling, processing, and reclamation" and review "best practices approaches." The committee has interpreted this charge to be forward looking—to describe what is presently in place and to look to the future in its description of best practices for future regulation of any uranium mining, processing, and reclamation that may occur in the Commonwealth of Virginia. While acknowledging that U.S. federal and state agencies have had extensive experience in attempting to remediate sites that were contaminated by past poor practices, the report does not delve into these past practices nor does it focus on the applicable regulations and programs that address the remediation of such sites.

For a number of reasons, the laws, regulations, and policies governing uranium mining, processing, reclamation, and long-term stewardship activities in the United States are neither well integrated nor transparent. Because of the way in which these laws, regulations, and policies were developed, gaps in coverage exist. First, the relevant laws and regulations were enacted or promulgated over the past 70 years, and were most commonly created after a crisis (e.g., uranium mill tailings contamination at early processing sites) or to address a particular situation, or contaminant, that is not unique to activities involving uranium mining, processing, reclamation, or long-term stewardship. Second, the missions of the agencies involved, and the laws they administer, vary considerably. The regulatory reach of the USNRC has traditionally been focused on radiological issues such as the use of the atom for energy generation and limitations on radiation doses to the public. In contrast, the USEPA's mission is the prevention of pollution, and the protection of public health and the environment through laws and regulations that are media-specific. Uncontrolled radiation releases are one source of environmental contamination requiring control. Worker safety and protection laws, such as the Mine Safety and Health Act and the Occupational Safety and Health Act, concentrate on employee health and the elimation of workplace hazards. Third, the laws, regulations, and policies (especially for environmental protection) are media- or activity-specific, and as a result are spread across agencies and consequently are not integrated and can be incomplete. For example, the standards applicable to uranium in air are covered by a different law and different regulations than standards applicable to uranium in water; and in the area of worker protection, three agencies share the responsibility to protect occupational health. In each of these situations, the rules for information sharing, public participation, and enforcement—it they exist at all—are different. Fourth, regulations promulgated for these activities have frequently been challenged in court, and the subsequent litigation

BOX 7.1
Regulatory Environment for Uranium-Related Activities in Canada

Almost all uranium mining, processing, and reclamation activities (as well as other activities involving radionuclides) in Canada are under the jurisdiction of the Canadian Nuclear Safety Commission (CNSC). Canada's Nuclear Safety and Control Act states,

> *"Any work or undertaking constructed for the development, production or use of nuclear energy, or for the mining, production, refinement, conversion, enrichment, processing, possession or use of a nuclear substance … is declared to be a work or undertaking for the general advantage of Canada."* (Section 71)

The CNSC is an independent, quasi-judicial executive agency. The Canadian Nuclear Safety and Control Act, which replaced a series of older Canadian laws dating back to the 1940s, established the CNSC in 2000. There are also other federal laws that apply to uranium mining, processing, and reclamation, including the Canadian Environmental Assessment Act and the Canadian Environmental Protection Act. As a result, CNSC employs a joint regulatory strategy—involving both Health Canada and Environment Canada—in decision making.

Provincial laws also apply to uranium mining, processing, and reclamation. For example, provincial laws applicable to water use would apply to any mine that seeks to withdraw groundwater. In addition, provinces have the authority to regulate and monitor exploration activities.

Environmental Assessment

The Canadian Environmental Assessment Act requires that any project requiring a CNSC license must undergo an environmental assessment. The CNSC must review, and make a decision regarding, the environmental assessment (EA) before any project license is issued. The EA process is flexible, and the requirements depend upon the nature of the project. It is the responsibility of the CNSC to determine the extent and nature of, and establish guidelines for, the EA. If a project is likely to have significant adverse environmental effects, a comprehensive study is likely to be required. If a project is deemed to have few or minor environmental

and court decisions have affected the way that regulations have been written and interpreted. Fifth, the nature of cooperation and coordination between the state and federal governments varies by law and agency. The programs of states that have signed agreements with the USNRC (i.e., Agreement States) are provided technical assistance and are subject to review for their continued adequacy.[2]

[2]See http://www.nrc.gov/about-nrc/state-tribal.html; accessed November 2011.

impacts, a relatively simple environmental screening process is undertaken. However, a screening-level assessment can be used for complex issues and can also lead to more extensive regulatory review.

It is the responsibility of the applicant to carry out the technical studies required by the assessment process. The applicant must consult with the public and Aboriginal peoples about the project and its technical studies. The CNSC prepares the EA report, and has the discretion to hold a public hearing to make its final decision about whether the project can proceed.

For comprehensive environmental assessment studies, a public consultation is mandatory. The CNSC must report to the federal minister of the environment regarding the public input. A project can be referred by the CNSC or the environment minister to a review panel for further discussion in the event that public concerns are substantial, or potentially significant environmental consequences are possible. If a panel is established, a public hearing is required. The federal government provides funding to facilitate public participation in the panel proceedings. The CNSC makes the final decision as to whether a project will proceed.

After Approval and Licensing—
Protecting Workers, Citizens, and the Environment

Under the Canadian Environmental Protection Act, Environment Canada has classified as toxic all uranium and uranium compounds that are contained in effluents from uranium mines and mills. However, the federal government has chosen to manage uranium and uranium compound risks under its Nuclear Safety and Control Act. A set of regulations has been promulgated under this act that cover uranium mines and mills.

In addition, in describing the information required for licensing, these regulations place monitoring obligations on licensees, authorize inspections, and impose penalties for noncompliance. Additional regulations have been promulgated to protect workers and the public from radiation and other hazards. Every licensee is required to implement a radiation protection program, and the annual limit on public radiation exposure is 1 milliseivert. Lower doses than this regulatory standard are commonplace because licensees are required to ensure that the radiation dose is “as low as reasonably achievable” (ALARA). The CNSC has also established regulations regarding to the safe and secure transportation of radioactive materials such as yellowcake.

Similarly, the programs of states with delegated authority from the USEPA are assessed under a state review framework that allows the USEPA to evaluate these programs consistently.[3] In contrast, some state activities, such as the regulation of uranium mining on nonfederal lands, have no direct federal counterpart and therefore receive no comparable federal guidance and scrutiny. In addition, the

[3]See http://www.epa.gov/compliance/state/srf; accessed November 2011.

BOX 7.2
Regulatory Process for Uranium Mining, Processing, and Reclamation in Colorado

Colorado has a long history of metal mining, including uranium mining. Uranium mining in Colorado first began after the discovery of radium around the turn of the 20th century, and it continued until the discovery of a rich vein of uranium ore in the Congo in the 1920s. The uranium produced by this mine supplanted uranium from other sources, including from Colorado, and it was not until the 1930s and 1940s that uranium mining recommenced in earnest in the state.

Uranium mining in Colorado accelerated in the 1940s with the expansion of the atomic weapons project as part of the war effort (Figure 7.1). The Manhattan Engineer District established an office in Grand Junction, Colorado, for uranium mining, extraction, and recovery; much of this early uranium processing occurred at abandoned metal mines. Considerable uranium ores coexist with vanadium in an area of Colorado known as the Uravan Mineral Belt, and mines in this area usually produce both uranium and vanadium. Today, the Uravan Belt contains over 1,200 historic mines that produced 63 million tons of uranium and 330 million pounds of vanadium from the late 1940s to the late 1970s (CO DRMS, 2011).

Mining techniques used in the middle 20th century were very crude by today's standards, and little attention was paid to waste disposal and reclamation. Mine

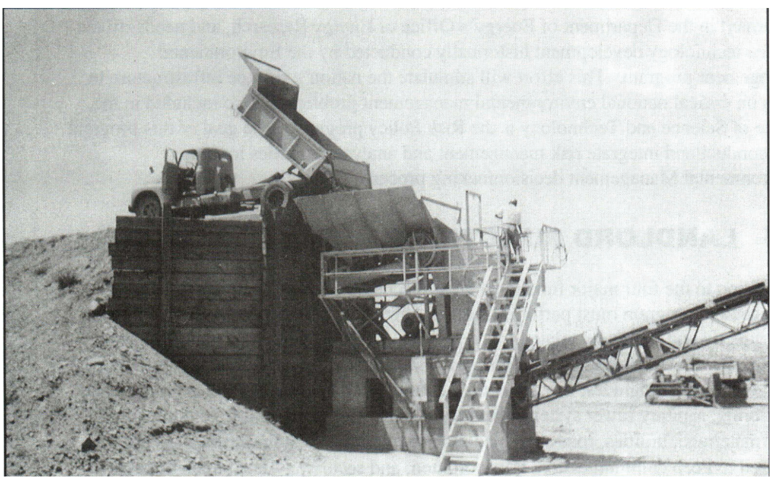

FIGURE 7.1 Uranium mining by the U.S. Atomic Energy Commission in Colorado, 1958. Uranium mining expanded dramatically in the United States after World War II, from 38,000 tons in 1948 to 5.2 million tons in 1958— nearly all of it for nuclear weapons production. SOURCE: USDOE Office of Environmental Management.

sites were abandoned once ore veins were exhausted; tailings piles were left unprotected, and raffinate—wastewater from the processing facilities—was discarded as surface water.[a] These activities resulted in environmental pollution and potential population health risks. In addition, health and safety standards to protect workers were either nonexistent or not enforced. Miners were exposed to very high levels of radon, and lung cancer rates among uranium miners were much higher than rates of lung cancer in the general population. This was particularly the case with disadvantaged and Native American populations, for example, members of the Navajo nation.

The mining and processing activities, especially those around Grand Junction, Colorado, created a legacy of pollution because of the use of uranium mill tailings as fill and for other purposes (Figure 7.2). Although uranium processing facilities were regulated by the Atomic Energy Commission following passage of the Atomic Energy Act in 1946, uranium mill tailings were not yet regulated under any federal or state laws. While the Grand Junction mines and processing facilities were active, tailings were used as fill for a number of purposes, including roadbeds, cement mixing, and home construction. As a result, radioactive pollution was a common problem, and over 4,000 residential and commercial properties

continued

FIGURE 7.2 Excavation of uranium mill tailings from a residential septic system, Grand Junction, Colorado, 1993. SOURCE: USDOE Office of Environmental Management.

BOX 7.2 Continued

were contaminated and eventually needed remediation.[b] The problems in Grand Junction[c] led to the passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978. Among other things,[d] UMTRCA expanded the definition of "byproduct material" to include uranium mill tailings, and required the U.S. Nuclear Regulatory Commission (USNRC) to regulate these tailings, clean up the tailings at inactive and/or abandoned mines, and set standards for active processing facilities.

As of June 2011, Colorado has 34 licensed uranium mines; none of these mines is presently producing ore. One mill (Piñon Ridge) has recently been licensed in Colorado but is not yet processing ore. Several former mines and mills, including the Lincoln Park Mill and the Uravan Uranium Mine, were sued by the State of Colorado for natural resources damages and are now—or have been—listed on the National Priorities List (NPL) established by the USEPA under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund). Cleanup activities at these sites have been ongoing and expensive. The 680-acre Uravan site was first listed in 1986. The site has since been cleaned up, and the tailing cells have been closed and capped, but the site remains under a radioactive materials license and is still on the NPL.[e] Postclosure efforts to delist the site from the NPL are ongoing; once delisted, the site will be transferred to the U.S. Department of Energy (USDOE). The Lincoln Park Mill site sits on 2,600 acres of land and is owned by the Cotter Corporation. It is located about 1.5 miles from the Cotter Uranium Mill, which holds a uranium recovery license. The site was first listed on the NPL in 1984, and cleanup is still under way.[f] Both Uravan and Cotter Corporation will require Records of Decision for the CERCLA delisting process.

Colorado's Permitting and Licensing Processes

Because Colorado is an Agreement State, the USNRC is not directly involved in licensing activities. The terms of its agreement with Colorado give the USNRC certain oversight and review functions. However, the state regulates—and has licensing authority for—uranium recovery operations such as in situ leaching/in situ recovery (ISL/ISR) and traditional uranium processing. The state requires a radioactive materials license for ISL/ISR mines, and its mine permitting process is under the jurisdiction of the Division of Reclamation, Mining and Safety (DRMS) of the Department of Natural Resources. ISL/ISR activities are regulated both by DRMS and the Colorado Department of Public Health and Environment (CDPHE).

Colorado's permitting and licensing procedures have evolved in parallel with technological advances in the mining industry and the recognition of the legacy of environmental problems from previous mines. Permitting of a uranium mine in Colorado requires numerous permits from the county, DRMS, and the Bureau of Land Management (on federal land), an environmental assessment,[g] an environmental protection plan, a stakeholder process, and bonding requirements. The Colorado Mined Land Reclamation Act of 1976 requires companies that are planning to conduct uranium mining operations to file for a reclamation permit with the

state's Mined Land Reclamation Board. The board carries out the mandates of the Mined Land Reclamation Act and works with the DRMS to implement reclamation laws and regulations. Recent amendments to the law established new rules to protect Colorado's groundwater during in situ uranium mining and revised existing rules on information disclosure during prospecting activities.[h]

Companies applying for a license to process uranium in Colorado undergo an application procedure that lasts at least 14 months.[a] First, the company must submit a radioactive materials license application and an environmental impact assessment (EIA) to the CDPHE Radiation Management Unit. Once the application is determined to be complete, the company must hold two public meetings to allow public comment on the application and the EIA. The relevant county may comment formally about perceived impacts to the community and environment, and local government may also have land-use or other regulations applicable to the project. County commissioners may request up to $50,000 from the applicant to review the EIA, and the commissioners' comments on the EIA must be submitted to the CDPHE within 90 days of the first public meeting.[i] The CDPHE then determines whether the license is rejected, issued as requested, or issued with certain conditions. Additional hearings are held if the applicant challenges the license conditions. In addition to obtaining the Radioactive Materials License, the applicant is also required to obtain permits for (1) discharge to surface water or for surface runoff from disturbed areas and (2) emissions from the site and to control dust from construction activities.

Piñon Ridge Facility License

In January 2011, the CDPHE approved a license application by Energy Fuels Resources Corporation to begin constructing a uranium mill in Piñon Ridge, in the Paradox Valley of southwestern Colorado. The proposed mill would be the first uranium/vanadium mill built in the United States since the 1980s. During the review process, CDPHE considered various technical documents and hundreds of stakeholder comments, as well as consulting with other regulatory agencies.[j] It produced an analysis of the applicant's EIA that reviewed geological, hydrological, chemical, and radiological parameters; various potential social, economic, and transportation impacts; and the proposed offsets or mitigation to the impacts identified. The CDPHE analysis confirmed that the applicant met requirements to assess the impacts to waterways, groundwater, and public health, and adequately considered the long-term impacts of the licensed activities and potential alternatives to those activities.

In August 2011, the company requested permission from the CDPHE to defer its remaining financial assurance payments until March 2012. The CDPHE approved this request, and amended the company's radioactive materials license to reflect a financial warranty of $11 million—to be paid prior to, and during, facility construction—for the decommissioning of the mill after it is closed.[k] The facility is designed to remain in operation for 40 years. CDPHE has continued to review and update the long-term care requirements to reflect changed cost estimates—which are based on a worst-case scenario—to ensure that the costs to implement the

continued

BOX 7.2 Continued

preapproved decommissioning and reclamation plan are not paid from taxpayer funds.[k]

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[a]Presentation by P. Egidi, Colorado Department of Public Health and the Environment, to the committee in Boulder, CO, March 23, 2011.

[b]See http://www.cdphe.state.co.us/hm/umtra/rpumtramgtplan.pdf.

[c]See, e.g., http://www.cdc.gov/niosh/ocas/pdfs/sec/gjoo/gjooer-175.pdf; accessed September 2011.

[d]UMTRCA also authorized the U.S. Environmental Protection Agency (USEPA) to set generally applicable environmental standards at uranium (and thorium) mill tailings sites and vicinity properties, which it did in 40 CFR Part 192. These standards apply at all such facilities that are licensed by the U.S. Nuclear Regulatory Commission (or an Agreement State). The USNRC's authority over remediation of tailings and residual radioactive material at inactive sites extended only to sites that were active (licensed) at the time UMTRCA was enacted or thereafter. The 24 inactive mill tailings sites designated in Title I of UMTRCA were the sole responsibility of the U.S. Department of Energy and so remain.

[e]http://www.cdphe.state.co.us/hm/rpuravan.htm.

[f]See http://epa.gov/aml/amlsite/npl.htm; accessed October 2011.

[g]See http://www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/grand_junction_field/PDF.Par.16552. File.dat/WhirlwinMineEAfinal.pdf.

[h]See http://mining.state.co.us/UraniumMininginColorado.pdf.

[i]See http://www.cdphe.state.co.us/hm/rad/rml/recoveryregs.pdf; accessed October 2011.

[j]See http://www.cdphe.state.co.us/hm/rad/rml/energyfuels/index.htm; accessed October 2011.

[k]See http://www.cdphe.state.co.us/release/2011/082311.pdf; accessed December 2011.

U.S. experience in uranium mining, processing, and reclamation over the past two decades has been limited, with little conventional uranium mining activity in the United States since the late 1980s. As noted in Chapter 4, in 2008 the United States accounted for less than 3 percent of worldwide uranium production. Chapter 3 also notes that there are currently five operating ISL/ISR plants in Texas, Nebraska, and Wyoming, and at least a dozen other ISL/ISR projects are being developed or are partially permitted and licensed.

The U.S. Energy Information Administration reported that at the end of 2010, only one uranium conventional processing facility was operating in the United States, with three other existing mills on standby (USEIA, 2011a). Because of the geological environment of uranium occurrences in Virginia, the committee has concluded that ISL/ISR techniques are not appropriate for uranium recovery in the Commonwealth (see Chapter 3). In the following sections, the committee has focused on conventional uranium mining and processing and sought to describe as clearly as possible the system of laws, regulations, and policies that apply to underground and open-pit mining and conventional uranium processing, and to ancillary activities such as reclamation and long-term stewardship.

FEDERAL LAWS, REGULATIONS, AND POLICIES

This section contains descriptions of the most significant federal laws, regulations, and policies that are applicable to uranium mining, processing, reclamation, and long-term stewardship, and notes the particular federal agencies that are charged with their implementation. Laws, regulations, and policies applicable to public participation and involvement are discussed at the end of this chapter in a separate section. As discussed in the chapter's introduction, these laws, regulations, and policies are neither well integrated nor transparent. As a result, this patchwork of laws, regulations, and regulatory responsibilities creates problems and challenges. These include (1) an increase in the amount of time and resources that potential licensees must expend to understand the system so that they are able to apply for permits and licenses and to meet technical requirements; (2) considerable difficulty and barriers for members of the public who wish to understand and participate in the permitting and licensing processes; (3) coordination issues among state and federal agencies and staff; and (4) obtaining the necessary technical expertise to understand both the radiological and nonradiological risks, and the requirements for their mitigation.

Uranium Mining

Under the Mining Law of 1872, as amended, mining on federally owned land is subject to federal regulation. This law requires that individuals who seek to mine on public land meet requirements regarding claim staking, maintenance, and patenting. Uranium mining authorized under the 1872 Mining Law must comply with the regulations of the federal agency managing the land; for example, the Department of Agriculture has established a series of requirements that apply in national forests. Agencies reviewing mine applications on federal lands must comply with the National Environmental Policy Act (NEPA), and, accordingly, it is likely that any mining on federal lands would require a full environmental impact statement (EIS) before a license to mine would be approved. There is no federal law that specifically applies to uranium mining on privately owned land, except for federal regulation of worker health and safety, and therefore Virginia would be responsible for regulating uranium mining activities on all nonfederal lands within the state.[4]

Although the federal government does not directly regulate uranium mining activities on lands that are not owned by the federal government, its laws regarding water pollution, air pollution, employee protection, and waste management do apply. The Clean Air Act (CAA) establishes a national emissions standard for

[4]In situ leaching/in situ recovery (ISL/ISR) is regulated by the USNRC or an Agreement State because it is treated as a joint mining and processing operation. As noted earlier, ISL/ISR is unlikely to be appropriate for uranium extraction in Virginia, and as a result, its coverage in this chapter is cursory and incomplete.

radon-222 that is applicable to underground mines.[5] Using its authority under the CAA, the USEPA promulgated 40 CFR Part 61, Subpart B, to protect the public and the environment from radon emissions to the ambient air from underground uranium mines. For underground mines of >10,000-tons per year production, it sets a limit on the emission of radon designed to ensure that no member of the public in any year receives an effective dose of more than 10 millirem (mrem) per year.

The Safe Drinking Water Act (SDWA) does not apply directly to underground or open-pit mines or effluent from such mines, although SDWA underground injection control regulations are triggered if ISL/ISR techniques are used. However, the SDWA does require that facilities that provide drinking water limit the amount of radionuclides in the water. Under the Federal Water Pollution Control Act, more commonly known as the Clean Water Act (CWA), the USEPA regulates discharges from open-pit and underground uranium mines. Its regulations, in 40 CFR Part 440, Subpart C, set discharge requirements for new uranium mines for uranium, zinc, pH, total suspended solids, radium, and chemical oxygen demand.[6]

The Mine Safety and Health Act establishes worker protection standards for miners (see Table 7.1). Under this act, mine operators must obtain a permit in order to operate, and among other requirements, the mine operator must obtain approval for a ventilation plan and roof control program and comply with all monitoring protocols and record-keeping procedures. These standards also include limitations on airborne contaminants (e.g., radon, silica, and diesel particulate matter) and protection against physical hazards such as noise. A hierarchy of controls approach is applied—engineering controls are strongly preferred over administrative controls, which are preferred over personal protective equipment such as respirators. The Mine Safety and Health Act requires inspections for underground mines four times per year; surface mines must be inspected two times per year. Mine inspectors have authority to order a withdrawal of workers from all or part of a mine.[7]

The Mine Safety and Health Administration (MSHA) has promulgated regulations that set a maximum yearly radon exposure of 4 WLM for underground mining;[8] this exposure limit is discussed in Chapter 5. These standards require periodic monitoring, recordkeeping, and the use of controls to limit exposure whenever possible. MSHA has a local presence in Virginia for both coal-mining and noncoal-mining activities. The Virginia District Office of the MSHA's coal mining program is located in Wise County, with field offices in Wise and Buchanan counties. The Southeast District Office of MSHA's noncoal mining

[5]National Emission Standards for Hazardous Air Pollutants (NESHAP), 40 CFR Part 61, Subpart B. See also 40 CFR Part 68; section 112(r) of the CAA.

[6]See 40 CFR § 440.34(a).

[7]See 30 CFR Part 62; also based on the presentation by J. Weeks, Mine Safety and Health Administration, to the committee in Washington, D.C., November 15, 2010.

[8]See 30 CFR § 57.5038.

TABLE 7.1 Health and Safety Regulations and Standards Applicable to Uranium Mines

Substance	Applicable Regulations	Exposure Standard
Silica (quartz)		100 μg/cm^3 per 8 hours
Noise	MSHA 30 CFR § 62.120 Action Level	85 dBA over 8 hours
	MSHA 30 CFR § 62.130 Permissible Exposure Level	90 dBA over 8 hours
	MSHA 30 CFR § 62.130 Maximum Exposure Level	115 dBA
Diesel particulate matter	30 CFR § 57.5060	
Radon	30 CFR §§ 57.5038 and 57.5039	4 WLM/year; 1 WL total
Gamma radiation	30 CFR § 57.5047(d)	5 rem/year

SOURCE: Compiled from cited regulations.

program is located in Birmingham, Alabama; its Virginia field office is located in Staunton, Virginia.

The USEPA[9] has prepared information about technically enhanced, naturally occurring radioactive materials, or TENORM, which "are any naturally occurring radioactive materials not subject to regulation under the Atomic Energy Act whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the natural state by human activities" (NRC, 1999a, pp. 1-2). Although the USEPA does not have the statutory authority under the AEA to directly regulate TENORM, it has authority under other statutes to regulate TENORM emissions that impact air and water quality. Under the Resource Conservation and Recovery Act (RCRA), Congress gave the USEPA the authority to study the impacts of uranium mining wastes and develop regulations (using other statutory authorities) to eliminate hazards.[10] The USEPA's TENORM-related activities have focused on studying TENORM sources, categorizing their potential hazards, and working to coordinate with parties, such as the states and tribes, that have the authority to regulate.

Security can be a concern during mine development and construction. Because of the chemicals present during these activities (i.e., ANFO, the mixture of ammonium nitrate and fuel oil used for blasting), security is necessary to keep trespassers out and to prevent theft of explosives and hazardous chemicals. Because the uranium is diffusely distributed within the rock, theft of enough uranium ore to cause a threat to public health and safety is unlikely. During mining activities, security concerns at surface pit or underground uranium mines parallel security concerns at non-uranium mines.

[9]See http://www.epa.gov/radiation/tenorm/.
[10]See 42 USC §§ 6921 (b)(3)(a) and 6982(f).

Guidance for underground mine emergency plans has been compiled by the National Institute for Occupational Safety and Health (NIOSH). The first few moments are critical in any underground mining incident (Kowalski-Trakofler et al., 2010). Through interviews with focus groups of individuals involved in response to underground mining emergencies, the numerous lessons learned have been compiled to help guide the emergency planning process. Because of the inherently dangerous situations present in underground mines, particular attention to key issues such as communication and information gathering in the first moments of an emergency can lead to better outcomes. Leadership and trust are essential, and can be enhanced with training and drills (Kowalski-Trakofler et al., 2010). Emergency planning is one of the areas where compliance with regulations is not sufficient; mine owners have an obligation to go beyond the regulations to inculcate emergency planning into every aspect of mine operation.

Uranium Processing

There are a range of federal laws that apply to uranium processing, which includes processing and the other physical and chemical treatment processes that ultimately lead to the production of yellowcake. The key statutes that provide environmental control and worker protection over uranium recovery are

- Federal Water Pollution Control Act (or Clean Water Act) (CWA),
- Clean Air Act (1963) (CAA),
- Safe Drinking Water Act (1974) (SDWA),
- Atomic Energy Act (1954) (AEA),
- Mine Safety and Health Act (MSH Act), and
- Uranium Mill Tailings Radiation Control Act (UMTRCA).

The AEA, enacted by Congress in 1954, regulates the civilian development, use, and control of nuclear energy. The AEA gives the USNRC broad regulatory authority; it is the primary regulatory agency for all facilities that hold a USNRC license. The USNRC also administers substantial portions of UMTRCA. As its name implies, this law applies to uranium tailings and is therefore applicable to uranium processing activities.

The USNRC has established standards for the protection against radiation (10 CFR Part 20) that are applicable to processing facilities. The USNRC licensing program (10 CFR Part 40) incorporates the 10 CFR Part 20 requirements and requires that the licensed facility monitor employee exposure and levels of radiation in effluents to the outside environment, as well as demonstrate that it has the training experience and proper materials to handle uranium. USNRC's Part 20 standards require that facilities assure that the total effective dose to individual members of the public from the facility does not exceed 0.1 rem (1 milliSievert) in a year. Before any license is granted, the USNRC must prepare

an EIS that examines, among other things, baseline environmental conditions, tailings disposal options, and costs and benefits. The agency must review the license every 5 years, and no license will terminate until the processing facilities are decommissioned.

The USNRC allows states to assume control of uranium processing through its Agreement State program. Under this program, a state can enter into an agreement with the USNRC if the state establishes a regulatory program based on regulations that are equivalent to, *or more stringent than,* the USNRC regulatory licensing program. The USNRC must review these standards every 2 years. In 2009, Virginia became an Agreement State for regulating source material, special nuclear material, and byproduct material except uranium mill tailings. The Committee understands that Virginia might seek Agreement State status for regulating uranium processing if Virginia were to lift its ban on uranium mining and processing. In the event that Virginia does not seek Agreement State status for this program, the USNRC would regulate uranium processing in the state.

Processing facilities must also comply with a series of environmental and worker safety regulations. For environmental standards, air, water, and other regulations apply. To protect against air pollution, the USNRC and the USEPA share responsibility for regulating radioactive gas emissions. The USEPA establishes the standards, while the USNRC implements and enforces them for its licensees. The USEPA has promulgated 40 CFR Part 61, Subpart W, to protect the public and the environment from the emission of radon from uranium mills and their tailings.[11] This standard limits the radon emissions rate to 20 picocuries per square meter per second, and requires that new tailings impoundments meet one of the two following requirements:

1. There are a maximum of two impoundments in operation at any time (including existing impoundments), and they cannot be more than 40 acres; tailings management and disposal is by phased disposal.
2. Tailings are immediately dewatered and disposed of, with no more than 10 acres uncovered at any time. Operators must also follow applicable requirements in 40 CFR § 192.32.

EPA has formed a workgroup to review and possibly revise Subpart W. On November 10, 2011, a revised risk assessment for radon emissions from operating mill tailings was released.[12] This risk assessment provides an analysis of the radiation dose to the reasonably maximally exposed individual and the population

[11]The USEPA has also promulgated NESHAP regulations for disposal of uranium mill tailings (40 CFR Part 61, Subpart T) and NESHAP regulations for underground uranium mines (40 CFR Part 61, Subpart B).

[12]See http://www.epa.gov/rpdweb00/docs/neshaps/subpart-w/historical-rulemakings/subpart-w-risk.pdf; accessed November 2011.

dose, with their associated risks, at three existing conventional mine/mill sites, five ISL/ISR facilities, as well as at two generic mine/mill sites. The maximum radon release at each of these facilities was used to calculate the radiation dose based on computer models, taking into account the distribution of population living within 80 km of the facility and the prevailing meterological conditions. The resulting doses (and risks) were then compared with regulatory limits. Chapter 5 contains a more detailed discussion of this risk assessment. This information will be useful for the USEPA's decision making on whether the standard needs to be revised; a decision is expected in January 2012.

USEPA's general NESHAP requirements, described in 40 CFR Part 61, apply as well; these NESHAP requirements cover monitoring and construction approval and contain definitions. USEPA's Subpart B NESHAP requirements, found at 40 CFR Part 61,[13] set a limit on the emission of radon from underground uranium mines to ensure that no member of the public in any year receives an effective dose of more than 10 mrem/year. Owners/operators of every mine must calculate the effective dose and report it to USEPA annually.

USEPA and USNRC also share responsibility for regulating water pollution. The USEPA's authority under the CWA allows it to set industrial discharges for pollutants, and its regulations generally cover radionuclides. However, the CWA regulations exclude all source, byproduct, and special nuclear material, as those terms are defined by the AEA. As a result, contaminants falling into these categories are regulated by the USNRC under 10 CFR Parts 20 and 40. The USNRC sets an effluent limitation and requires its licensees to apply the ALARA principle to keep releases as low as reasonably achievable. For other contaminants such as chemical oxygen demand, zinc, radium and total suspended solids, the USEPA's CWA regulations contain a "no discharge" standard: *"Except as provided in paragraph (b) of this section, there shall be no discharge of process wastewater to navigable waters from mills using the acid leach, alkaline leach or combined acid and alkaline leach process for the extraction of uranium or from mines and mills using in situ leach methods"* (40 CFR § 440.34(b)(1)). However, this very strict standard is tempered considerably by the exception referenced in the first clause of the regulations: "*In the event that the annual precipitation falling on the treatment facility and the drainage area contributing surface runoff to the treatment facility exceeds the annual evaporation, a volume of water equivalent to the difference between annual precipitation falling on the treatment facility and the drainage area contributing surface runoff to the treatment facility and annual evaporation may be discharged subject to the limitations set forth in paragraph (a) of this section.*" (40 CFR § 440.34(b)(2)).[14] In summary, the regulations provide an exception to the zero-discharge rule, and because of Virginia's climate

[13]See http://www.epa.gov/rpdweb00/neshaps/subpartb/index.html; accessed November 2011.

[14]See http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=022ea7ae4a49a6938b6ccd94c552d024&rgn= div6&view=text&node=40:30.0.1.1.16.3&idno=40.

this exception would apply—when annual precipitation exceeds evaporation, the facility can discharge an amount of process water that is equal to this difference. Before discharge, this process water must be treated to meet the statutory standards set out in 40 CFR § 440.34.

Uranium mill tailings are covered by UMTRCA. Uranium mill tailings contain radium, which decays to produce radon, and the radium in these tailings will not fully decay for thousands of years. Typical environmental problems arising from mill tailings are radon emanations, wind-blown dust dispersal, and the leaching of contaminants—including radionuclides and heavy metals—into surface waters and groundwaters. UMTRCA gives USEPA the responsibility for issuing generally applicable standards for control of uranium mill tailings. In 1983, USEPA issued standards for both Title I (inactive) sites and Title II (active and new) sites. In November 1985, the USNRC changed its regulations in 10 CFR Part 40, Appendix A, to be consistent with USEPA Title II standards. Since 1985, various changes have been made to Part 40 for the Title II sites. Most recently, the USNRC amended its Part 40 regulations to improve decommissioning planning to reduce the likelihood that any facility now in operation could become a legacy site. These changes include enhanced financial assurance and monitoring requirements that are intended to detect large volumes of contamination that might not exceed a dose limit.[15]

Radiation protection standards for workers at USNRC-licensed facilities are developed and enforced by the USNRC, and these must be consistent with other federal regulatory programs protecting workers, including federal standards that limit worker exposure and requirements to monitor radiation levels and maintain records. MSHA and the Occupational Safety and Health Administration (OSHA) might also have a regulatory role at USNRC-licensed processing facilities. One interagency agreement and two memoranda of understanding (MOUs) allocate responsibilities among these parties. The USNRC and OSHA have entered into a MOU that spells out their respective responsibilities, addressing the four groups of hazards. The USNRC generally covers that first three hazards and OSHA covers the fourth category:

- Radiation risk produced by radioactive materials
- Chemical risk produced by radioactive materials
- Plant conditions that affect the safety of radioactive materials and therefore present an increased risk to workers, such as a fire or explosion that might release radioactive contaminants
- Plant conditions that result in an occupational risk, but do not affect the safety of licensed radioactive materials, such as exposure to toxic (non-radioactive) compounds or other industrial hazards

[15]See 76 Fed. Reg. 35,512-35,575 (June 17, 2001).

In addition, OSHA and MSHA have entered into an interagency agreement to coordinate activities under the Mine Safety and Health Act and the Occupational Safety and Health Act. The agreement notes that MSHA has the authority to promulgate and enforce safety and health standards for workers in mining-related operations and preparation and processing. OSHA has authority over all working conditions of employees engaged in business, except those conditions regulated by other federal agencies. The agreement spells out in detail the relationship between these two entities. Generally, MSHA has jurisdiction over all mineral extraction and processing, including the lands, facilities, equipment, and other property used in these activities. OSHA has authority over ancillary operations. The agreement notes that "there will remain areas of uncertainty regarding the application of the Mine Act,[16] especially in operations near the termination of the processing cycle and the beginning of the manufacturing cycle."[17]

Finally, the USNRC and MSHA have entered into a MOU to describe their approach to regulating processing activities that fall under both the Mine Safety and Health Act and the Atomic Energy Act. The agencies will each carry out their responsibilities separately, and in the interest of administrative efficiency will cooperate regarding the promulgation and enforcement of safety and health standards, use compatible inspection procedures and techniques, and exchange information regarding enforcement actions.[18]

Security, Accountability, and Transportation

Security at a uranium processing facility has several aims. First, a facility must establish general security, which involves keeping intruders out by the use of fencing, guards at gates, alarms, etc. Second, a facility must establish "insider" security by engaging in background checks on employees, fingerprinting, and similar measures. Third, a facility must establish material control requirements for secure handling of radioactive materials, dangerous chemicals, and any other items used in uranium processing that could create a health or safety hazard. Since the terrorist attacks on September 11, 2001, the USNRC has increased its focus on security at radioactive materials facilities.

An assortment of chemicals are used during the recovery of uranium from ore. Sulfuric acid, high-purity kerosene, tertiary amines, ANFO, alcohol, and peroxide or ammonia could be employed during these processes. If the processing facility and mine are contiguous, the same physical security system (fencing, guards) could protect both the mine and processing areas. If they are located at some distance from each other, appropriate security systems for the types of

[16]The Federal Mine Safety and Health Act of 1977, as amended.

[17]See http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=MOU&p_id=222; accessed November 2011.

[18]See 45 Fed. Reg 1315 (January 4, 1980).

materials present at the individual facilities would need to be designed. Because the end product of the processing operation is yellowcake, appropriate accountability for the uranium that is concentrated from the ore must be maintained. Security measures are also necessary to prevent theft of the yellowcake. Following theft of radioactive materials from a processing facility in Namibia, access controls, use of biometrics (retinal scanners), and closed-circuit TV systems were recommended as increased security measures.[19] Security measures also include physical separation of drums, tamper-proof seals, state-of-the-art fencing and intrusion detection, and other security measures that would prevent theft. USNRC licensees must take precautions to ensure safe and secure handling of both source material and byproduct material. According to USNRC regulations, to transfer a radioactive material, a licensee must verify that the transferee has a license to possess that type, form, and quantity of source or byproduct material (10 CFR § 40.51). Each licensee that is authorized to export natural uranium in amounts exceeding 500 kg, other than in the form of ore or ore residue, must notify the USNRC at least 10 days in advance. Under the licensing provisions in 10 CFR Part 20, the licensee is required to prevent unauthorized removal or access of all licensed materials that are stored in controlled or unrestricted areas. For materials not in storage, the licensee must maintain constant surveillance. Signs must be posted and containers must be labeled, and recordkeeping is also required. If any materials are lost or stolen, reporting to the USNRC is required.

The product of the uranium processing facility (yellowcake) is not subject to the integrated source management system that the USNRC has proposed to track high-risk radioactive sources. This Web-based licensing verification system is intended to provide a comprehensive program for security and control of radioactive material, but it is not intended to include yellowcake because it is not considered to present a high risk.[20]

The United States has an agreement with the International Atomic Energency Agency (IAEA), implemented through 10 CFR Part 75, that covers uranium processing facilities and mines. Material accounting and control information is collected by the covered facilities through the USNRC, and the facilities are subject to inspection by IAEA personnel on an ad hoc, routine, or special inspection basis (10 CFR § 75.8).

Packaging design requirements are regulated by the USNRC, and it has responsibility for establishing requirements for the design and manufacture of packages for radioactive materials (10 CFR Part 71) The U.S. Department of Transportation (USDOT) regulates shipments while they are in transit, and sets standards for labeling and smaller quantity packages in accordance with its haz-

[19]Wikileaks: see http://rogerpociask.posterous.com/wikileaks-us-evaluation-of-uranium-mine-secur; accessed September 2011.

[20]See http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-appe.html; accessed September 2011.

ardous safety materials program. Before any shipment can occur, the shipper is required to review the package certificate of compliance to determine if any testing or maintenance is required. The shipper may be required to check or change package seals and other components, or perform leak testing. In addition, the shipper must take radiation measurements at specific locations on and around the package to make sure that the radiation levels are below the required limits.

The shipper must also meet USDOT's requirements for shipment of the radioactive material (e.g., USDOT, 2006), including route selection, vehicle condition and placarding, driver training, package marking, labeling, and other shipping documentation. The department's Pipeline and Hazardous Materials Safety Administration publishes training materials for individuals who may be involved in transport of radioactive materials.[21]

Reclamation

When mining and processing activities at a site are completed, the site will undergo a decommissioning process. For mining sites on privately owned land, state laws determine how the site is reclaimed, and it is likely that site ownership will remain with the private landowner after reclamation. For mining sites on state or federal land, state or federal reclamation laws and regulations dictate how the land is reclaimed, and it is probable that the state or federal governments will retain ownership of these sites. For uranium processing facilities, reclamation activities are dictated by the site license. During this process, the facility will seek to terminate its USNRC (or Agreement State) license, and will work with USNRC, USEPA, the state, and other applicable regulatory authorities as well as the surrounding community to prepare the site so that uranium mining and processing activities can end. License termination involves safely removing a facility from service and reducing residual radioactivity to a level that permits the license to be terminated. The nature and scope of the decommissioning and reclamation process will depend upon several factors, including the amount of waste material to be left on-site, the nature of the site contamination, and the planned future uses for the site.

A key feature of site decommissioning plans involves the treatment, stabilization, and control of uranium mill tailings. UMTRCA gives the USNRC the authority to regulate tailings, which are defined in the law as byproduct material, and the USNRC (and/or an Agreement State) oversees project management and technical review for decommissioning and reclamation (Appendix A to 10 CFR Part 40). These regulations require that every license applicant include in its license application how it will dispose of and manage tailings, and Appendix A lists 13 technical criteria that licensees must address. These criteria state that

[21] See http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Hazmat/Hazmat%20 Training/HowTo Radioactive.pdf; accessed September 2011.

the general goal in siting and design is the permanent isolation of tailings and associated contaminants without the need for ongoing maintenance. The prime option for tailings disposal is placement belowgrade, in either mines or specially excavated pits. In certain cases, placement belowgrade might not be possible. If abovegrade disposal is used, it must be demonstrated that the tailings will be isolated from natural erosion to the same extent as belowground placement. The technical criteria incorporate USEPA's 40 CFR Part 192 (Subparts D and E) groundwater protection standards and monitoring requirements. Standards for airborne emissions must also be followed.

The regulations also require financial surety arrangements that provide sufficient funds for decontamination and decommissioning of the site (also see Box 7.3). The amount of funds must be based on USNRC-approved cost estimates, and include decommissioning, demolition, and reclamation expenses. A variety of financial surety instruments are acceptable, but self-assurance is not allowed.

BOX 7.3
World Bank Guidance on Financial Surety

The World Bank has developed a guidance document based on financial surety systems that apply in a number of countries. The World Bank estimates that closure of medium-size open-pit and underground mines costs $15M, while closure of open-pit mines operating for over 35 years, with large waste and tailings facilities, can cost upward of $50M. The guidelines outline considerations for governmental requirements, including

- Adequate financial resources must be available for reclamation and closure as well as redress for any impacts that a mining operation may cause to wildlife, soil, and water quality.
- The instrument chosen for the financial surety must be reasonably liquid and accessible to the regulators should funding be needed to initiate reclamation and remediation in case of operator default.
- The guarantor's financial health must be screened to ensure that it will not default.
- The public should be involved and informed, because it will bear the cost of remediation if there is a default.

Finally, the World Bank states clearly that financial surety is not a substitute for an operator's legal liability to clean up the site.

Long-Term Stewardship

A site that contains uranium mill tailings that is licensed by the USNRC or an Agreement State cannot undergo license termination until it meets certain closure and postclosure requirements, and either a state government or the federal government—typically, the USDOE—assumes ownership of the site. These sites are administered under the provisions of a general USNRC license (see 40 CFR § 40.28). To obtain this general license, the USNRC requires that the prospective licensee develop a long-term surveillance plan (LTSP) for the site.

Appendix A of 10 CFR Part 40 specifies closure and postclosure obligations, which include requirements for siting and design of the tailings pile, cover performance, and financial surety for decommissioning, reclamation, and long-term surveillance. When the USNRC has terminated the specific license or has concurred in an Agreement State's termination of a specific license, the reclaimed tailings areas are transferred to either USDOE, another federal agency designated by the President, or the state in which the site is located, for custody and long-term care under the general license provisions of 10 CFR § 40.28. According to section 40.28, an LTSP must include (1) a legal description of the site to be transferred; (2) a description of the final site conditions, including characterization of existing groundwater conditions, that is sufficiently detailed to provide a baseline for assessing the seriousness of future changes; (3) a description of the long-term surveillance program, including proposed inspection frequency, frequency and extent of groundwater monitoring if required, appropriate constituent concentration limits for groundwater, inspection personnel qualifications, inspection procedures, and recordkeeping and quality assurance procedures; (4) the criteria for follow-up inspections in response to observations from routine inspections or extreme natural events; and (5) the criteria for instituting maintenance or emergency measures. Under 10 CFR § 40.48(b), there is no termination of the general license under which the LTSP is carried out. At present, the Office of Legacy Management has control over six such sites; this number will probably increase as ongoing site reclamations are completed. Ultimately, the Office of Legacy Management could manage as many as 27 of these sites.[22]

The USNRC licensing regulations of 10 CFR Part 40, Appendix A, Criterion 12 state that

> final disposition of tailings, residual radioactive material, or wastes at mining sites should be such that on-going active maintenance is not necessary to preserve isolation. At a minimum, inspections must be conducted by the government agency responsible for long-term care of the disposal site to confirm its integrity and to determine the need, if any, for maintenance and/or monitoring.

The various federal regulatory authorities applicable to uranium mining,

[22] See http://www.lm.doe.gov/pro_doc/references/framework.htm; accessed September 2011.

processing, reclamation, long-term stewardship, transportation, and security are summarized in Table 7.2.

STATE AGENCIES, LAWS, REGULATIONS, AND POLICIES

As noted above, because a mining moratorium is in place, Virginia does not have a law that specifically addresses uranium mining, and its agencies have not been authorized to establish programs to regulate uranium mining under other state laws. However, certain activities—such as air and water emissions control—are regulated by Virginia at other hard-rock mining sites. State law authorizes several state agencies to lease state lands for mineral production. Rental and/or royalty rates can be established by these agencies. Leases on certain submerged lands require that a royalty be collected (Virginia Code Ann. §§ 28.2-1208, 53.1-31). At present, there are 460 nonfuel mines (e.g., quarries, sand and gravel pits, and other surface and underground mining operations) in Virginia that cover 66,000 acres. These mines are permitted and regulated by the Division of Mineral Mining within the Department of Mines, Minerals and Energy.[23]

This section describes the Virginia state agencies that are active, and have authorities over, the regulatory areas that could be applicable to uranium mining. In the event that the uranium mining moratorium were to be lifted, it is likely that state agencies would play a role in regulating underground or surface uranium mining facilities.[24] Table 7.3 summarizes these agencies and their possible areas of responsibility.

Local ordinances might apply to proposed uranium mines and processing facilities; requirements contained in zoning codes can play a role in site preparation and facility construction can trigger the need for soil erosion and sediment control. Local governments and/or soil and water conservation districts (Code of Virginia §§ 10.1-560 et seq.) could have applicable programs.

Department of Mines, Minerals and Energy

The Virginia Department of Mines, Minerals and Energy (VA DMME) is under the jurisdiction of the Secretary of Commerce and Trade. Laws governing VA DMME are contained mainly within Title 45.1 of the Code of Virginia. It is the lead agency responsible for administering state laws and regulations regarding mining and is part of the state grant program of the U.S. Department of Labor's MSHA. Among other areas, the VA DMME has state jurisdiction over miner health and safety and over geological surveying. It has approximately 230

[23]See http://www.dmme.virginia.gov/DMM/divisionmeralmining.shtml; accessed September 2011.

[24]The Commonwealth of Virginia's Department of Mines, Minerals and Energy has reviewed and granted one permit for uranium exploration at Coles Hill in Pittsylvania County.

TABLE 7.2 Summary of Key Federal Authorities for Uranium Mining, Processing, Reclamation, Long-Term Stewardship, Transportation, and Security

Activity	Federal Department or Agencies Involved	Nature of Involvement	State-Federal Relationship (if any)
Mining	Mining Act of 1872, as amended, covers mining on federal lands, along with regulations of agency owning land	Regulations regarding claim staking, maintenance, patenting, and EIS	If mining takes place on federal land, the federal agency supervising the land would be the lead agency
	No federal laws specifically address mining activities on non-federally owned lands[a]	N/A	State is the sole regulator
	U.S. Environmental Protection Agency (USEPA)	Regulations cover water discharges, air discharges; guidance on overburden (TENORM) has also been published[b]	Air and water programs can be delegated to the state, and the state can enact regulations on overburden
	Department of Labor, Occupational Safety and Health Administration (OSHA)	An interagency agreement between OSHA and MSHA addresses jurisdictional questions	States can operate OSHA-approved plans (OSH Act § 18), but must operate under state law
	Department of Labor, Mine Safety and Health Administration (MSHA)	Regulations cover miners and processors. An interagency agreement between OSHA and MSHA addresses jurisdictional questions.	MSHA has a state grant program that distributes funds to state programs responsible for miner safety and health; states can enact mining laws that are at least as stringent as, or more stringent than, MSHA
	Department of Health and Human Services, National Institute for Occupational Safety and Health	Guidance for emergency planning	

Processing	U.S. Nuclear Regulatory Commission (USNRC)	Regulates uranium recovery processes (e.g., uranium processing facilities) and activities at these facilities such as worker health and safety	Programs can be relinquished to an Agreement State
	USEPA	Regulations cover water discharges, air discharges, land disposal, contamination cleanup	Programs can be delegated to state
	Department of Labor, OSHA	Regulations cover some on-site workers (not miners) (workers in the processing facility, truck drivers, equipment operators); jurisdictional issues explaining how occupational and worker health are divided among USNRC, OSHA, and MSHA are described in a series of interagency memoranda of understanding and agreements	States can operate OSHA-approved plans (OSH Act §18), but must operate under state law
	MSHA	Has authority to regulate processing along with the NRC; jurisdictional issues are spelled out in a series of interagency memoranda of understanding and agreements	
	U.S. Department of Transportation	Regulations cover transportation of chemicals, explosives, yellowcake	
Reclamation	USEPA	Authorities for cleanup (Resource Conservation and Recovery Act [RCRA] and Comprehensive Environmental Response, Compensation, and Liability Act (Superfund))	RCRA program can be delegated; Superfund is not delegated to states; authorities unlikely to be used unless there is a nonpermitted release from the site
	USNRC	License termination process and issuance of general license	State or federal agency can obtain a general license from the USNRC
	OSHA	Workplace safety	
Long-term stewardship	Federal or state government (for sites with uranium processing facility tailings)	Assume site ownership	Federal government or state government assumes ownership of processing sites with uranium mill tailings (see Uranium Mill Tailings Radiation Control Act (UMTRCA) § 202(a)(2)).

[a]Earlier text provides a fuller explanation of this point.
[b]See http://www.epa.gov/radiation/tenorm/.

TABLE 7.3 Commonwealth of Virginia Agencies Involved in Mining and Related Activities and Their Areas of Jurisdiction

Agency	Area of Jurisdiction/ Regulation	Statutory and Regulatory Authorities
Department of Mines, Minerals and Energy (VA DMME)	Major regulatory authority for mining operations	Major agency for mining regulation
Department of Labor and Industry (VA DLI)	Federal OSH Act, Virginia worker safety laws	Major state-level agency for worker health and safety
Department of Environmental Quality (VA DEQ)	Water, air, waste permitting	Delegated authorities under Clean Water Act, Clean Air Act, Safe Drinking Water Act (SDWA), Resource Conservation and Recovery Act
Department of Conservation and Recreation (VA DCR)	Stormwater discharge during mine construction; natural heritage program	Minor involvement, authorities assumed by VA DMME and/or VA DEQ once mining starts
Department of Health (VDH)	Safe drinking water, including private drinking water wells; source, byproduct, and special nuclear material regulations (Agreement State), excluding uranium processing	Delegated authority from USEPA to administer the federal SDWA; regulates placement and construction of private wells but does not monitor their water quality. Virginia's Agreement State program (which does not cover uranium processing facility tailings) is administered by VDH. It is the sole regulatory agency in Virginia with radiation expertise

employees and an annual budget of approximately $20 million (Spangler, 2011). VA DMME includes a Division of Mineral Mining, which handles noncoal mining activities—primarily rock, sand, and gravel mining. The division's workforce includes 10 inspectors and 2 supervisors.

VA DMME has indicated that if the uranium mining moratorium were to be lifted, the regulatory program for the mining operation would closely follow the model that was developed for reviewing the exploratory permit that authorized the recent drilling program conducted at the Coles Hill site (Spangler, 2011). More specifically, VA DMME indicated that it would pool expertise from its office and other state agencies (especially those with expertise in drilling, groundwater control, and air contamination protection), and it would make use of other state and national programs, for example, by applying aspects of existing regulations regarding hard-rock mining to uranium mining.

Virginia's hard-rock mining laws are set out in Title 45.1 of the State Code. Among other things, these laws require the issuance of a permit to mine before any activity is commenced, and a reclamation bond must be posted. According to the Virginia statutes, in applying for a permit to commence mining operations after exploration an applicant must

- review all leases and deeds to procure rights of entry;
- conduct a background assessment that reviews land use, as well as the historical and cultural value of the land;
- assess any necessary restrictions or provisions for removing tracts of land from mining;
- conduct public hearings to disseminate information and obtain input into the application; and
- establish standards for postmining land use that are consistent with the surrounding land.

In addition, the applicant must demonstrate financial surety, and the financial assurance must encompass all site activities and include postmining closure (Spangler, 2011). Once mining and other activities commence, the Commonwealth will inspect for compliance and safety, and additional inspections will take place in the event of an accident and/or worker injury. The VA DMME has the authority to issue closure orders and other orders to mine operators, but cannot assess civil penalties for health and safety violations.

In 2009, VA DMME reported that mining resulted in the removal of 56 million tons of minerals (Spangler, 2011).[25] In addition to the mining itself, VA DMME's Division of Mineral Mining also administers the reclamation regulations for mineral mining sites (Virginia Administrative Code, Title 4, Agency 25, Chapter 31). These regulations specify, for example, performance bond requirements, stabilization and revegetation procedures, and drainage and sediment control.

Department of Labor and Industry

Like VA DMME, the Department of Labor and Industry (VA DLI) comes under the jurisdiction of the Secretary of Commerce and Trade. VA DLI enforces the regulatory standards established in the federal Occupational Safety and Health Act (OSH Act) as well as state worker protection laws.[26] Between 2000 and 2010, Virginia had five fatalities in its noncoal mining industry.[27] VA DLI conducts

[25] Currently, there is no metal mining in Virginia, although metal mining has been carried out in the past. These figures represent mining in sand, gravel, and crushed stone.

[26] See http://www.doli.virginia.gov/vosh_enforcement/vosh_standards.html; accessed May 2011.

[27] See http://www.msha.gov/stats/charts/Allstates.pdf; accessed September 2011.

unplanned safety and health enforcement inspections in response to accidents, employee complaints, and referrals, as well as planned inspections in special-emphasis inspection programs and randomly scheduled inspections of high-hazard industries.[28] One of OSHA's special-emphasis programs is trenching and excavation.

Department of Environmental Quality

The Department of Environmental Quality (VA DEQ) comes under the jurisdiction of the Secretary of Natural Resources. Among other things, VA DEQ is responsible for water permitting (process wastewater and stormwater run-off from industrial activities) (Paylor, 2011; 9 VAC 25-31-10 and 40 CFR Part 440), air permitting, and RCRA permits. The VA DEQ also coordinates implementation of Virginia's environmental impact review requirement (Code of Virginia § 10.1-1188). State agencies are required to conduct an environmental impact review for the construction of state facilities whose cost is greater than or equal to $500,000. In addition, exploration for, and extraction of, minerals on state-owned lands require EISs.

VA DEQ sets water discharge limits using both water quality criteria and technology-based standards. In Virginia, water quality criteria are classified in three Tiers (I, II, and III) based on the quality of the receiving waters. Tier III is composed of "no-discharge" waters—absolutely no discharge is allowed. Tier II waters are high-quality waters where strict discharge standards are set; for example, the waters surrounding the Coles Hill site are Tier II waters. Tier I waters are less pristine. Water quality criteria are established using a mass balance and worst-case scenario assumptions (Paylor, 2011). The water quality criteria would apply to discharges of radionuclides (limits would be set at criteria for public water sources) and metals, including zinc, arsenic, copper, and selenium, as well as other potential contaminants. Under Virginia's delegated authority under the CWA, mines and processing facilities that discharge to state waters must obtain a National Pollutant Discharge Elimination Permit. The permit requires that monitoring be conducted twice a year for specific pollutants determined by the type of ore mined.

Virginia has committed to a policy of antidegradation of groundwater quality, which states

> if the concentration of any constituent in groundwater is less than the limit set forth by groundwater standards, the natural quality for the constituent shall be maintained; natural quality shall also be maintained for all constituents, including temperature, not set forth in groundwater standards. If the concentration of any constituent in groundwater exceeds the limit in the standard for that constitu-

[28] See http://www.doli.virginia.gov/whatwedo.html; accessed May 2011.

> ent, no addition of that constituent to the naturally occurring concentration shall be made. Variance to this policy shall not be made unless it has been affirmatively demonstrated that a change is justifiable to provide necessary economic or social development, that the degree of waste treatment necessary to preserve the existing quality cannot be economically or socially justified, and that the present and anticipated uses of such water will be preserved and protected. (Virginia Code § 62.1-44.4)

Current groundwater quality standards set no specific limit for uranium, but limits are set for the uranium daughters radium-226 and radium-228. Complete listing of the groundwater quality standards and groundwater criteria are provided in Tables 7.4 to 7.6).

Department of Conservation and Recreation

Like VA DEQ, the Department of Conservation and Recreation (VA DCR) comes under the jurisdiction of the Virginia Secretary of Natural Resources. VA DCR plays a minor role in regulating mining operations. It maintains jurisdiction over stormwater discharges during construction activities and oversees local soil erosion and sediment control programs, which include conducting inspections during construction. Stormwater management is transferred to VA DMME and VA DEQ when mining operations start.[29] VA DCR also administers the Commonwealth's natural heritage program.

Department of Health

The Department of Health (VDH) operates under the jurisdiction of the Secretary of Health and Human Resources. VDH enforces regulations and standards under the Virginia Public Water Supply law (Code of Virginia §§ 32.1-167 et seq.) and the federal SDWA. Its responsibilities include regulating aspects of private drinking water wells related to design, construction, and placement of wells, but do not include monitoring requirements.

The Division of Radiological Health within VDH has responsibility for regulating all machine sources of radiation (e.g., x-ray machines, particle accelerators) and all radioactive sources except uranium mines or processing facilities, performing radiation monitoring around certain fixed nuclear facilities in Virginia (i.e., the North Anna and Surry nuclear generating stations and Babcock and Wilcox nuclear operations group), maintaining a radiological emergency response team, maintaining a radon program to advise citizens about this health hazard, maintaining a radiation laboratory, and updating regulations regarding radiation.

[29] Presentation by D. Johnson, Virginia Department of Conservation and Recreation, to the committee in Richmond, February 7, 2011.

TABLE 7.4 Groundwater Standards Applicable in the Commonwealth of Virginia

Constituent	Concentration	Units
Sodium	270	mg/L
Foaming agents as methylene blue active substances	0.05	mg/L
Petroleum hydrocarbons	1	mg/L
Arsenic	0.05	mg/L
Barium	1	mg/L
Cadmium	0.0004	mg/L
Chromium	0.05	mg/L
Copper	1	mg/L
Cyanide	0.005	mg/L
Lead	0.05	mg/L
Mercury	0.00005	mg/L
Phenols	0.001	mg/L
Selenium	0.01	mg/L
Silver	None	
Zinc	0.05	mg/L
Chlorinated hydrocarbon insecticides		
Aldrin/dieldrin	0.003	µg/L
Chlordane	0.01	µg/L
DDT	0.001	µg/L
Endrin	0.004	µg/L
Heptachlor	0.001	µg/L
Heptachlor epoxide	0.001	µg/L
Kepone	None	
Lindane	0.01	µg/L
Methoxychlor	0.03	µg/L
Mirex	None	
Toxaphene	None	
Chlorophenoxy herbicides		
2,4-D	0.1	mg/L
Silvex	0.01	mg/L
Radioactivity		
Total radium (Ra-226 + Ra-228)	5	pCi/L
Radium-226	3	pCi/L
Gross beta activity[a]	50	pCi/L
Gross alpha activity (excluding radon and uranium)	15	pCi/L
Tritium	20,000	pCi/L
Strontium-90	8	pCi/L
Manmade radioactivity, total dose equivalent[b]	4	mrem/yr

NOTE; mg/L = milligrams per liter; µg/L = micrograms per liter; pCi/L = picocuries per liter; mrem/yr = millirem per year.

[a]The gross beta value shall be used as a screening value only. If exceeded, the water must be analyzed to determine the presence and quantity of radionuclides to determine compliance with the tritium, strontium, and manmade radioactivity standards.

[b]Combination of all sources should not exceed total dose equivalent of 4 mrem/yr.

SOURCE: 9 VAC 25-280-40.

TABLE 7.5 Groundwater Standards Applicable in the Commonwealth of Virginia by Physiographic Province

	Concentration			
Constituent	Coastal Plain	Piedmont & Blue Ridge	Valley and Ridge	Cumberland Plateau
pH	6.5-9	5.5-8.5	6-9	5-8.5
Ammonia nitrogen	0.025 mg/L	0.025 mg/L	0.025 mg/L	0.025 mg/L
Nitrite nitrogen	0.025 mg/L	0.025 mg/L	0.025 mg/L	0.025 mg/L
Nitrate nitrogen	5 mg/L	5 mg/L	5 mg/L	5 mg/L

SOURCE: 9 VAC 25-280-50.

TABLE 7.6 Groundwater Criteria

	Groundwater Criteria by Physiographic Province (mg/L)			
Constituent	Coastal Plain	Piedmont & Blue Ridge	Valley and Ridge	Cumberland Plateau
Alkalinity	30-500	10-200	30-500	30-200
Total dissolved solids	1,000	250	500	500
Chloride	50[a]	25	25	25
Sulfate	50	25	100	150
Total organic carbon	10	10	10	10
Color	15	15	15	15
Iron	0.3	0.3	0.3	0.01-10
Manganese	0.05	0.05	0.05	0.01-0.5
Sodium	100[a]	25	25	100
Fluoride	1.4[b]	1.4	1.4	1.4
Hardness	120	120	300	180

NOTE: Because natural groundwater quality can vary greatly from area to area for these constituents, enforceable standards were not adopted. These criteria are intended to provide guidance in preventing groundwater pollution. Groundwater criteria are not mandatory.

[a]It is recognized that naturally occurring concentrations will exceed this limit in the eastern part of the Coastal Plain, especially toward the shoreline and with increased depth.

[b]Except within the Cretaceous aquifer, concentration up to 5 mg/L and higher.

SOURCE: 9 VAC 25-280-70.

Regulatory Program Funding and Resources

Regulatory programs at the state level are supported by fees that are assessed on regulated industries. The fee structure is created to recover the cost of resources expended for implementing a regulatory agency's responsibilities, including staffing, training, and equipment. Since regulations must be developed prior to collecting fees, the initial development of regulations is usually not covered by fees, and if the uranium mining moratorium were to be lifted, then

the Virginia legislature would need to provide an appropriation to the regulatory agencies involved so that they could develop the expertise to write, implement, and enforce the regulations.

PUBLIC PARTICIPATION IN THE REGULATION OF URANIUM MINING, PROCESSING, AND RECLAMATION

Because of concerns about the off-site effects—negative or positive—of uranium mining and processing facilities on human and environmental health and welfare, members of the public often express interest in participating in the regulation of such facilities. Requirements for public participation—the two-way exchange between regulators and the public in advance of regulatory decisions so that the public can receive information and make comments—apply to both federal and state regulatory processes.

Opportunities under the current regulatory structure for public participation in the regulatory process for uranium mining and processing facilities are offered during the promulgation of regulations of general applicability, the licensing of particular facilities, and the development and approval of postclosure plans for facility reclamation and long-term stewardship.

Public Participation in Federal-Level Regulatory Decisions

Public participation in federal actions regarding uranium mining and processing is governed by various federal laws and regulations, including the Administrative Procedure Act (5 USC Chapter 5, Subchapter II), the National Environmental Policy Act (42 USC Chapter 55) (NEPA), and agency-specific laws and regulations. NEPA is often the statute that triggers the most substantial public input. As noted elsewhere in this chapter, the regulations of several agencies come into play with uranium mining and processing, and the formulation of these regulations would be required to adhere to federal public participation requirements.

For surface or open-pit mining on nonfederal lands, there is no federal requirement for an environmental impact analysis and no federal requirement for public participation. When considering a license application for an ISL/ISR process, or for a facility that will process uranium ore from an open-pit or a surface mining operation, the USNRC has public participation provisions for both the licensing process itself and the accompanying environmental review. In the prelicensing stage, members of the public are notified through various means, including the *Federal Register*, press releases, and local advertisements, that a license application has been received. If local interest is strong, the USNRC may hold public meetings in the vicinity of the proposed facility.[30] The degree of public participation allowed in a USNRC public meeting ranges from primar-

[30]See http://www.nrc.gov/about-nrc/regulatory/licensing/pub-involve.html.

ily observational to open discussion, depending upon the type of meeting; with major licensing applications, the USNRC also may post an opportunity to request a hearing.

A new major facility such as a uranium processing facility is also, as noted elsewhere in this report, subject to the requirements of NEPA. Typically, an environmental assessment (EA) is prepared first. The EA is a preliminary document that summarizes the potential environmental impacts to briefly provide sufficient evidence and analysis to help determine whether to prepare an EIS or a finding of no significant impact. If the EA indicates that the proposed facility could have a significant effect on the environment, a full EIS is then developed. USNRC regulations require that the USNRC conduct an EIS for all uranium processing facility licensing actions. The USNRC is thus required to hold public meetings, including open scoping meetings. These meetings are held in the vicinity of the facility; they provide information to members of the public and an opportunity for them to express their opinions, and they serve as a means to help the USNRC identify issues to be addressed in the EIS.

Public Participation in State-Level Regulatory Decisions

Public participation in state-level agency decisions is governed by the Virginia Administrative Process Act (Code of Virginia, Title 2.2, Chapter 40). In formulating regulations, this act specifies that each agency shall develop guidelines for soliciting the input of interested parties and that the agency, pursuant to its guidelines, *"shall afford interested persons an opportunity to submit data, views, and arguments, either orally or in writing to the agency, to include an on-line public comment forum on the Virginia Regulatory Town Hall, or other specially designated subordinate"* (§ 2.2-4007.02). The Virginia Regulatory Town Hall[31] is a Web-based means for agencies, boards, and secretariats to provide information on upcoming regulatory changes and for members of the public to submit comments electronically. The Administrative Process Act also specifies that agency guidelines are to set out any methods in addition to a "Notice of Intended Regulatory Action" for identifying and notifying interested parties, as well as a general policy for using standing or ad hoc advisory panels and for consulting with interested groups and individuals. The act does not speak directly to public participation in regulatory decisions regarding particular cases.

Regarding prospective public participation in permitting uranium mining facilities, the current practices of the Division of Mineral Mining (DMM) within VA DMME are relevant. Under state law (Code of Virginia § 45.1-184.1), an applicant to DMM for a new mineral mining permit must identify and notify adjacent landowners within 1,000 ft of the proposed facility boundary. According to DMM, no notification is required for a permit renewal or an expansion of the

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[31] See http://townhall.virginia.gov/.

original acreage.[32] The notified property owners then have 10 days to file written objections with the DMM director and/or request a public hearing regarding the proposed operation. According to DMM, the hearing is an informal "information gathering" forum in which people attending may present comments as well as evidence. The hearings officer then makes a written recommendation regarding the permit to the DMM director. Based on this recommendation and any additional information pursuant to the hearing, the DMM director issues a final order on the permit. This final order may be appealed to civil court in the city or county where the mine is located.

FINDINGS AND KEY CONCEPTS

The committee's analysis of the existing regulatory environment applicable to uranium mining and processing in Virginia has produced the following findings:

- ***The activities involved in uranium mining, processing, reclamation, and long-term stewardship are subject to a variety of federal and state laws that are the responsibility of numerous federal and state agencies.***
- ***Because the Commonwealth of Virginia enacted a moratorium on uranium mining in 1982, the state has essentially no experience regulating uranium mining and there is no existing regulatory infrastructure specifically for uranium mining.*** The state does have programs that regulate hard-rock mining and coal mining.
- ***There is no federal law that specifically applies to uranium mining on non-federally owned lands; state laws and regulations have jurisdiction over these mining activities.*** Federal and state worker protection laws, and federal and state environmental laws, variously apply to occupational safety and health, and air, water, and land pollution resulting from mining activities.
- ***At present, there are gaps in legal and regulatory coverage for activities involved in uranium mining, processing, reclamation, and long-term stewardship.*** Some of these gaps have resulted from the moratorium on uranium mining that Virginia has in place; others are gaps in current laws or regulations, or in the way that they are applied. Although there are several options for addressing these gaps, the committee notes that Canada and the state of Colorado have enacted laws and promulgated regulations based on best practices that require modern mining and processing methods, and empower regulatory agencies with strong information-gathering, enforcement, and inspection authorities. In addition, best practice would be for state agencies, with public stakeholder involvement, to encourage the owner/operator of a facility to go beyond the regulations to adopt international industry standards if they are more rigorous than the existing regulations.

[32]See http://www.dmme.virginia.gov/dmm/permitting&licensing.shtml.

• ***The U.S. federal government has only limited recent experience regulating conventional[33] uranium processing and reclamation of uranium mining and processing facilities. Because almost all uranium mining and processing to date has taken place in parts of the United States that have a negative water balance (i.e., dry climates with low rainfall), federal agencies have limited experience applying laws and regulations in positive water balance (i.e., wet climates with medium to high rainfall) situations.*** The U.S. federal government has considerable experience attempting to remediate contamination due to past, inappropriate practices at closed or abandoned sites.

• ***Under the current regulatory structure, opportunities for meaningful public involvement are fragmented and limited.*** Key points in the regulatory process for public participation include (1) the promulgation of regulations of general applicability, (2) the licensing of particular facilities, and (3) the development of postclosure plans for facility reclamation and long-term stewardship. Regarding (1), the current regulatory structure requires that members of the public who are interested in prospective uranium mining and processing in Virginia be aware of and respond to rulemaking by several different state and federal agencies. The Virginia Regulatory Town Hall could provide an online means of coordinating information and opinion exchanges about upcoming state-level regulatory changes pertinent to mining, but at present the Regulatory Town Hall does not offer transparent cross-agency coordination by topic. Regarding (2), the Division of Mineral Mining's explicit opportunities for public participation in licensing a mining facility currently are limited to adjacent landowners. The USNRC has a more robust approach to public participation in licensing a uranium processing facility. Its regulations require the USNRC to conduct an EIS, during which prelicensing public meetings or hearings will be held in the vicinity of the proposed facility. Regarding (3), there is no evidence at present that members of the public would be included in deliberations about postclosure plans at the time those plans would be implemented.

[33]Conventional mining and processing includes surface or open-pit mining, or some combination of the two, and their associated processing plants, but excludes ISL/ISR uranium recovery.

8

Best Practices

Key Points

- Uranium mining and processing have planning, construction, production, closure, and long-term stewardship phases, and best practice requires a complete life-cycle approach during the project planning phase. Planning should take into account all aspects of the process—including the eventual closure, site remediation, and return of the affected area to as close to natural conditions as possible—prior to initiation of a project. Good operating practice is for site and waste remediation to be carried out on a continuous basis during ore recovery, thereby reducing the time and costs for final decommissioning, remediation, and reclamation. Regular and structured risk analyses, hazard analyses, and operations analyses should take place within a structured change management system, and the results of all such assessments should be openly available and communicated to the public.
- Development of a mining and/or processing project should use the expertise and experience of professionals familiar with internationally accepted best practices, to form an integrated and cross-disciplinary collaboration that encompasses all components of the project, including legal, environmental, health, monitoring, safety, and engineering elements.

- Meaningful and timely public participation should occur throughout the life cycle of a project, so that the public is both informed about—and can comment upon—any decisions made that could affect their community. All stages of permitting should be transparent, with independent advisory reviews.
- Development of a comprehensive environmental impact statement for any proposed uranium mining and processing facility would be an essential element for public participation and the transparent sharing of information.
- A number of detailed specific best-practice documents (e.g., guidelines produced by the World Nuclear Association, International Atomic Energy Agency, and International Radiation Protection Association) exist that describe accepted international best practices for uranium mining and processing projects. Although these documents are by their nature generic, they provide a basis from which specific requirements for any uranium mining and processing projects in Virginia could be developed.
- Some of the worker and public health risks could be mitigated or better controlled if uranium mining, processing, and reclamation are all conducted according to best practices, which at a minimum for workers would include the use of personal dosimetry—including for radon decay products—and a national radiation dose registry for radiation- and radon-related hazards; and exposure limits lowered to at least the levels for radon, diesel gas and particulates, occupational noise, and silica hazards recommended by the National Institute for Occupational Safety and Health (NIOSH).
- A well-designed and executed monitoring plan, available to the public, is essential for gauging performance, determining and demonstrating compliance, triggering corrective actions, fostering transparency, and enhancing site-specific understanding. The monitoring strategy, encompassing baseline monitoring, operational monitoring, and decommissioning and postclosure monitoring, should be subject to annual updates and independent reviews to incorporate new knowledge or enhanced understanding gained from analysis of the monitoring data.
- Because the impacts of uranium mining and processing projects are, by their nature, localized, modern best practice is for project implementation and operations, whenever possible, to

provide benefits and opportunities to the local region and local communities.

- Regulatory programs are inherently reactive, and as a result, the standards contained in regulatory programs represent only a starting point for establishing a protective and proactive program for protecting worker and public health, environmental resources, and ecosystems. The concept of ALARA (as low as is reasonably achievable) is one way of enhancing regulatory standards.

The committee's charge requests that the report describe the best practices that would apply to any uranium mining, processing, and reclamation operations in Virginia. In responding to this charge and identifying and briefly describing these best practices, the committee is not implicitly endorsing or proposing that the moratorium should be lifted or that uranium mining or processing in Virginia should be undertaken.

Because the characteristics of any uranium mining or processing facility in the Commonwealth of Virginia would be highly dependent on the circumstances that would apply in any specific case—controlled in large part by the detailed geological character of an ore deposit and the characteristics of the local environment—a detailed compilation of internationally accepted best practices would undoubtedly include many that would not be applicable to a specific situation in Virginia. Accordingly, rather than assemble an encyclopedic compilation, the committee has outlined three overarching best-practice concepts, followed by specific suggestions for best practices that the committee's analysis has identified as likely to be applicable should the moratorium on uranium mining in Virginia be lifted.

The committee recognizes that should Virginia's uranium mining moratorium be lifted, mining and processing activities are very unlikely to commence for at least 5 to 8 years after the initial decision to permit uranium mining and processing (Box 8.1). Full use of this period will be essential for development of a regulatory culture that promotes environmental and human health protection, for instituting a broad range of human health and environmental baseline monitoring activities, for development of a robust legal and regulatory infrastructure, and to assemble a management team that is responsive both to the regulatory process and to the full range of citizen and stakeholder needs.

OVERARCHING BEST-PRACTICE PRINCIPLES

During committee deliberations, there were themes that recurred during the discussions, often transcending specific disciplinary areas, which are the focus of this section.

Complete Life-Cycle Planning and Regular Reevaluations

Development of a uranium mining and/or processing facility has planning, construction, production, closure, and long-term stewardship phases. The complete life cycle of the facility and its activities should be conceived as one integrated process from the start (i.e., when the design begins) to the end (i.e., when long-term stewardship starts). Good operating practice is for site and waste remediation to be carried out on a continuous basis during ore recovery, thereby reducing the time and costs for final decommissioning, remediation, and reclamation. Project management should not be stagnant, but should evolve in an iterative manner to take full advantage of international advances. Regular and structured risk analyses, hazard analyses, and operations analyses should take place within a structured change management system. The results of all such assessments should be openly available and communicated to the public. All stages of permitting should be transparent, with independent advisory reviews. In addition, ongoing communication with other facilities, both operating and in closure, is essential to capture lessons learned and incorporate them through an adaptive management approach to avoid public health or environmental consequences that were not anticipated at the outset of the project.

Need for Qualified Experts

Development of a mining and/or processing project should use the expertise and experience of professionals familiar with internationally accepted best practices, to form an integrated and cross-disciplinary collaboration that encompasses all components of the project, including legal, environmental, health, monitoring, safety, and engineering elements. As a corollary to the first best practice, above, this collaboration of highly qualified persons or organizations should incorporate experience that encompasses all stages of a project—design, operation, closure, and long-term stewardship. Although this best practice would apply generally throughout the United States, where no new uranium mines have been developed for decades and there is no experience with a positive water balance environment, this best practice is particularly important in Virginia where there is no background or local experience with uranium mining, processing, or reclamation.

BOX 8.1
Life-Cycle Analysis and Holistic Planning

The development of a regulatory infrastructure that can specifically focus on and specialize in the entire life cycle of any proposed uranium mine will undoubtedly be at first a lengthy political process and then a demanding regulatory buildup. The former will span different administrations and legislative cultures that may vary in policy view and political stamina. Moreover, the regulatory buildup may have to overcome established and entrenched regulatory cultures and increasingly limited resources. A generic scenario (Figure 8.1) would suggest that development of a comprehensive regulatory infrastructure might take at least 4 years. Concurrent development of the regulatory structure would need to occur at least by the early stages of the permitting phase, because the time to mine operations may be at least 6 years in this scenario. Note that recent experiences worldwide indicate that these time estimates are optimistic, and there can be delays for many reasons. The timing of both development of the regulatory structure and permitting are crucial, so that the convergence point results in a viable operation that is safe for public health and the environment. If the Commonwealth of Virginia chooses to simply rely on the existing regulatory agencies and the patchwork of existing applicable public health and environmental protection authorities, although many do not apply to uranium mining and production, then the time line to an operational mine and mill will be more dependent on the development of the mine and associated facilities themselves and be much less influenced by any infrastructural needs of the regulatory entities involved.

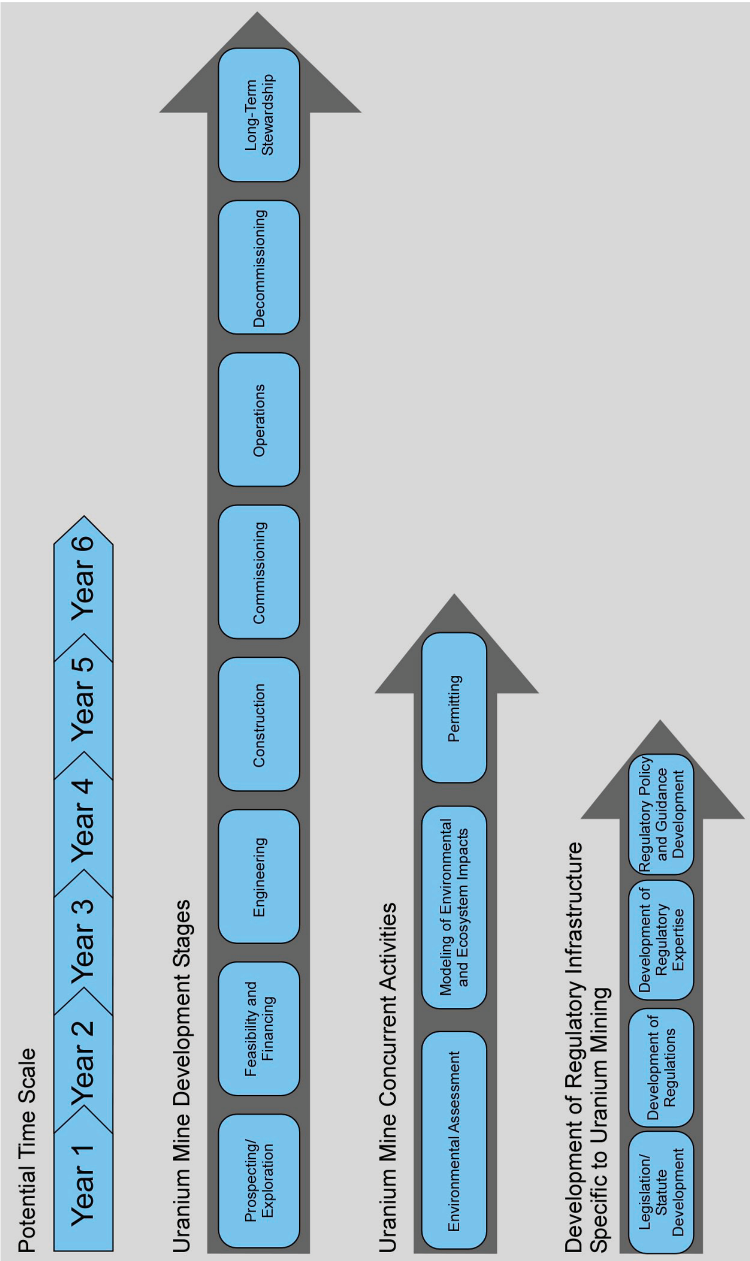

FIGURE 8.1 Possible stages and timing for development of a conceptual uranium mine as well as the stages and timing for development of a regulatory infrastructure specific for uranium mining and processing.

Transparency, Information Exchange, and Meaningful Public Involvement

Meaningful and timely public participation should occur throughout the life cycle of a project, beginning at the earliest stages of project planning. This requires creating an environment in which the public is both informed about, and can comment upon, any decisions made that could affect their community. One important contribution to transparency is the development of a comprehensive environmental impact statement for any proposed uranium mining and processing facility. Another requirement is that notice is given to interested parties in a timely manner so that their participation in the regulatory decision-making process can be maximized. This requirement would include substantial advance notice, including sufficient detail about the status of the project so that members of the public can easily understand the information that will be conveyed to them. The public should also be able to understand how the information they convey to the operators or regulators will be used in decision making. All stages of permitting should be transparent, with independent advisory reviews. As part of this best practice, the facility or regulatory agency should consider whether it is appropriate to appoint an ombudsman to facilitate communication. An additional important consideration is that because mining projects and mining impacts are by their nature localized, modern best practice is for project implementation and operations to—wherever possible—provide benefits and opportunities to the local region and local communities.

Literature Resources

Although not seeking to endorse or recommend any specific best practices in existing literature, the committee noted that many of the overarching themes that it identified coincide with concepts put forward by the World Nuclear Association (WNA; see Appendix C), the International Atomic Energy Agency (IAEA, 2010), and the International Radiation Protection Association (IRPA; see Appendix D). The WNA, based in London, is an international industry group that has the goal of promoting nuclear energy, and a mission to seek to foster interaction among top industry leaders to help shape the future of nuclear power. The IAEA, based in Vienna, Austria, is an autonomous international organization that seeks to promote the peaceful use of nuclear energy. It is not under the direct control of the United Nations, but it does report to both the U.N. General Assembly and Security Council. The IRPA, based in France, is an international professional association focused on radiation protection. Although the WNA, IAEA, and IRPA documents are by their nature generic, they provide a basis from which specific requirements for any uranium mining and processing projects in Virginia could be created.

SPECIFIC BEST PRACTICES

At a more specific level, best-practice guidelines that encompass a diverse range of issues that should be considered during planning for any uranium mining and processing project in Virginia are described below (e.g., the development of a site-specific conceptual and/or numerical model and baseline environmental characterization; comprehensive analysis, and predictive assessment of potential off-site water, soil, air, and ecological impacts, with specific attention to acid mine drainage control; design standards that address potential natural disasters; spill prevention and response strategies; the utility of personal dosimeters, etc.). These examples are not intended to be an exhaustive compilation of best-practice guidelines, but rather represent a range of issues and suggestions that the committee considers important for operational and regulatory planning if the moratorium on uranium mining is removed. In addition, two specific examples are presented in more detail—on the overarching best practices for closure and postclosure and best practices for emergency management.

Best Practices for Minimizing Potential Health Effects

This section presents a series of best practices for minimizing the potential adverse health effects, described in Chapter 5, resulting from radiation exposure, exposure to diesel particulates, hearing loss, and silica exposure.

Radiation

Uranium mines and processing facilities should have a radiation program in place that safeguards the health and safety of workers as well as the general public. Radiation doses and risks should be kept as low as is reasonably achievable (ALARA), while taking economic and social factors into account. Best practices also include the use of personal dosimetry for radon decay products, rather than area monitors, to record workers' exposures to radiation. A continuous personal alpha activity dosimeter is already in routine use outside the United States for uranium mining and processing operations. Such dosimetry represents a best radiation safety practice, as opposed to relying on area level sampling as has been typical in uranium mining in the United States. When calculating a dose to an individual, all potential sources of exposure should be identified (Chambers, 2010). In developing best practices for setting radon decay product exposure limits for uranium miners and processors, it is important to consider that NIOSH recommended in 1985 a permissible exposure limit 75 percent lower than the current U.S. Department of Labor's Mine Safety and Health Administration (MSHA) and Occupational Safety and Health Administration (OSHA) exposure limit of 4 working level months (WLM) per year, and that the NIOSH director at that time stated that a permissible exposure limit as low as 1 WLM/yr did not

satisfy NIOSH's commitment to protect the health of all the nation's miners. Unlike Canada, although the USNRC does require tracking of dose, a formal national U.S. radiation dose registry does not currently exist. A radiation dose registry represents a best practice, allowing the tracking of individual workers as they move from site to site.

Diesel Particulates

Reducing diesel exposure-related risks requires engineering controls to guarantee adequate ventilation and to reduce emissions at their source by ensuring that newer diesel engine technologies are used that generate lower amounts of particulate and other combustion byproducts. Appropriate industrial hygiene assessments of potential exposures should be carried out on a routine basis.

Hearing Conservation

Protection from the adverse effects of excess occupational noise exposure has been previously summarized by NIOSH; a cornerstone of such practices is the recognition that exposure at levels currently allowable under OSHA regulations will result in noise-induced hearing loss (NIOSH, 1988). NIOSH has also generated extensive recommendations for injury reduction and risk control that reflect best practices in that regard.

Silica

The appropriate control measures for silica hazard abatement include the use of wet as opposed to dry operations, enclosure of toxicant point sources that present a potential exposure hazard, local ventilation to draw dust away from the worker's breathing zone, and appropriate respiratory protection including externally supplied air for jobs that have the potential for high exposure. For workers with ongoing silica exposure—in particular, exposures approximately half the lower level of recommended exposure limits—ongoing health surveillance programs are appropriate. The NIOSH recommended exposure limit for respirable silica dust is considerably lower (in the direction of health protection) than current U.S. Department of Labor MSHA or OSHA legally enforceable standards as currently promulgated.

Best Practices for Environmental Monitoring

A well-designed and -executed monitoring plan is essential for gauging performance, determining and demonstrating compliance, triggering corrective actions, fostering transparency, and enhancing site-specific understanding. Additionally, a well-designed and adequately supported monitoring program

can lead to better-informed management, public, and regulatory decisions. The three main phases of a monitoring strategy include baseline monitoring, operational monitoring, and decommissioning and postclosure monitoring. Ideally, the monitoring strategy (including details of sampling locations, frequency, monitored parameters, sampling methods) would be developed through collaboration among facility staff, technical experts, regulatory officials, community members, and public interest groups to meet the overall goals of the many stakeholders. A multitiered strategy that follows a rigorous sampling protocol, where the mining and processing facility, local community groups, and local government agencies conduct parallel monitoring programs, can be an effective strategy to address multiple concerns and maintain trust. Accordingly, before any uranium mining and/or processing facility is established, modern best practice requires that a comprehensive baseline environmental monitoring and assessment program be conducted, incorporating three components:

1. Baseline environmental characterization (both on- and off-site), including chemical, physical, and radioactive elements of the water, air, and soil; biological indices (e.g., benthic index); habitat characterization; and identification of species or communities of special interest that could be affected by construction or operation. The establishment of natural background for uranium, its decay products, and other nonradiological contaminants associated with uranium mining is essential in order to compare operational and postreclamation levels (see also NCRP, 2011). The length and frequency of baseline monitoring needs to be of sufficient duration to capture the natural variability (both inter- and intra-annual) of measured parameters. The spatial extent of baseline monitoring should encompass the mine site and offsite areas with potential for environmental impacts. Because Virginia is a positive water environment (i.e., precipitation exceeds evapotranspiration on an annual basis), particular attention should be paid to downgradient groundwater resources and downstream water resources that could be affected by water pollutants released from the mining operations.
2. Development of a site-specific conceptual and/or numerical model to guide development of a site-specific monitoring program.
3. A comprehensive analysis and predictive assessment of potential off-site water, soil, air, and ecological impacts, such as that performed for an environmental impact assessment.

In addition, best practice is to undertake an assessment of the appropriate mitigation and remediation options that would be required to minimize predicted environmental impacts, including but not limited to

- ***Acid mine drainage (AMD) control***. The production of AMD is a serious and nearly ubiquitous environmental problem associated with many types of mining, with the potential to adversely affect downstream water resources. Iden-

tifying the amount of metal sulfides present in the ore or waste rock is a first step in mitigating potential impacts; uranium ores containing lesser amounts of metal sulfides can be mined and processed more safely with lesser impacts on downstream systems. To reduce the production of AMD and the associated leaching of heavy metals and radionuclides, very careful handling (including temporary storage and landfilling) is necessary for materials containing metal sulfides. Strict segregation and burial of such wastes in low-permeability strata might be considered as an option. Discharge of all wastewaters from mining and processing operations into a carefully engineered and appropriately sized treatment facility should be used to neutralize AMD and precipitate contaminants prior to release to receiving waters off-site to meet discharge standards.

- ***Tailings and waste management***. Modern tailings management facilities differ significantly from those used in the past. Engineered tailings facilities for both belowgrade and partially abovegrade facilities employ, among other things, geomembranes, leachate collection systems, and hydraulic isolation using a combination of extraction wells and materials of contrasting permeability (see Golder Associates, 2008). In Virginia's positive water balance environment, best practices would not include long-term tailings storage aboveground. Instead, the tailings could be emplaced and compacted so that they have a much lower permeability than the surrounding aquifers to lessen the potential for groundwater contamination. Tailings management systems should be designed to withstand the extreme event scenarios that could reasonably occur at a site.
- ***Treatment of all water discharged***. All water generated from dewatering and ore processing should be treated in an on-site water treatment facility and held in an on-site facility pending verification that it meets water quality criteria prior to being discharged to the environment (CNSC, 2010). Modern industry practice is for much of the water from dewatering and ore processing to be recycled within the processing plant, often numerous times, prior to eventual discharge.
- ***Spill prevention and response strategies***. Best practices should emphasize sound management practices and administrative and engineering controls that prevent the release of hazardous substances to the environment, such as employee training, periodic inspections of storage tanks, adequate secondary containment, and standard operating procedures for routine operations and maintenance. Both regulatory and mine- and processing-site employees should be empowered to report and address deficiencies that occur. In addition, response plans, trained personnel, and emergency equipment should be at hand to respond to any incident that occurs (see also Box 8.2).
- ***Dust control.*** During construction and throughout all the other uranium mining and processing steps where dust may be generated, control measures would include dust suppression systems, spraying or wetting dust, use of tactifiers, and washing construction equipment before it leaves the site. Underground mines should have extensive exhaust systems to protect workers from exposure

to dust and radon, and air pollution control systems can be installed on vents to prevent dispersion to ambient air. Control measures for uranium mills include enclosure of dusty operations, dust collection systems, dust suppression systems, spraying or wetting dust, and ventilation systems specific to conveyor belts and other rock-moving systems. Fugitive dust from overburden, uranium ore that is not economically viable for processing, and waste piles should be controlled through capping or other means (Martin Marietta Laboratories, 1987).

A comprehensive environmental monitoring and assessment program should be conducted throughout all phases of project development, from construction through closure (see also Box 8.3). The monitoring and assessment program should include chemical, physical, and biological sampling and analysis. Monitoring during the operational lifetime should cover the same spatial extent as described for baseline monitoring. The postclosure monitoring plan *may* need to be amended (e.g., different spatial extent or temporal frequency) to account for site reclamation efforts and cessation of active operations. Specific components of a best-practices monitoring and assessment program include the following:

- ***Public involvement***. Public involvement in the design and implementation of the monitoring program is valuable to build credibility and ensure that stakeholders' concerns are addressed. In addition to the primary on- and off-site monitoring program, funding should be provided to potentially affected communities to conduct independent monitoring of attributes of particular concern to the community.
- ***Annual independent monitoring data assessment and review***. An independent annual assessment and trending analysis should be performed to test the accuracy of predictions and, if need be, to recommend modifications to the operations and remediation practices. The annual assessment can also be used to refine the predictions and adaptively modify the monitoring plan as needed. For example, on the basis of data collected, this independent review panel might recommend expanding the monitoring of pathways or potential impacts that appear more significant and to reduce monitoring of pathways or potential impacts that appear of lesser importance.
- ***Transparency and accessibility***. All data and independent reviews should be available to the public, and this information should be discussed at annual public meetings for transparency and to build credibility.

Site-specific conceptual and numerical models are essential to quantify the understanding of the full earth system, determine appropriate mitigation and response strategies, and develop and modify a monitoring plan. Therefore, these models need to undergo annual updates and independent reviews, to incorporate new understanding gained from analysis of the monitoring data or new knowledge (e.g., changes to process design and operation).

BOX 8.2
Overarching Best-Practice Principles of Emergency Management

Emergency management planning is crucial to all aspects of uranium mining, processing, reclamation, and long-term stewardship. Emergency management plans should cover how to prepare for, mitigate, respond to, and recover from an emergency. Systematic emergency management preparations are needed for both on-site uranium mining and processing activities and off-site transport of materials.

There are common elements in emergency management for any industrial facility. Emergency response planning is always a work in progress. The emergency plan should be viewed as a living document, with annual reviews to incorporate lessons learned at the facility and from similar facilities worldwide to make continuous improvements in safety. Although planning is critical, there are other elements that are equally important: training, exercising, testing equipment, and coordination with off-site responders. Best practices dictate that linkages between people and equipment need to be well established before an emergency occurs.

The types of emergencies that should be considered for planning purposes range from natural events (e.g., earthquakes, hurricanes, floods) to manmade events (e.g., spills or releases of hazardous substances, whether due to human error or terrorism). The initiating event could be from a variety of reasons, but response to the emergency can be standardized, so that regardless of the cause, the event can be properly handled. The root cause of the emergency can be investigated after the situation is stabilized.

The U.S. Federal Emergency Management Agency (FEMA) recommends a four-step process for planning for emergencies.[a] The first step is to establish an emergency planning team, including representatives from all aspects of the processing facility or mine—management, labor, engineering, safety/environmental, public affairs, human resources, security, legal, community relations, finance, and purchasing.

The second step is to identify the hazards that require planning and the resources that are available for response. This step should include consultation with off-site agencies such as fire, police, hospitals, utilities, and community service organizations such as the Red Cross. A vulnerability analysis that determines the probability and potential impact of each emergency will help guide the planning process. The vulnerability analysis will be informed by historical data for emergen-

Best Practices for Regulation and Oversight

Regulatory programs are inherently reactive. Accordingly, standards contained in regulatory programs represent only a starting point for establishing a protective and proactive program for defending worker and public health, and the environment. Embracing the concept of ALARA[1] is one way of enhancing

[1]ALARA (acronym for 'as low as is reasonably achievable') is defined as "means making every

cies that have occurred in the area, as well as using geographic information for proximity to seismic faults, dams, floodplains, other industrial facilities with hazardous materials, etc. Technological failure of mining and processing processes and human error should be considered. The assessment of impact should include human impact, property impact, and business impact. The resource list should include internal and community resources.

Step three is to develop the plan, which should include the following:

- Direction and control—who is in charge under various emergency conditions
- Communication—warning systems, notification systems
- Life safety—evacuation, accountability, shelter
- Property protection—emergency shutoffs, fire suppression, water-level monitors, preservation of vital records
- Community outreach—training, exercising with counterparts, mutual aid agreements, community service, public information, media relations
- Recovery and restoration—essential equipment repair, contractual services, continuity of management, insurance, employee support, resumption of operations
- Administration and logistics—maintenance of written plan, notification lists, equipment and supplies, backup utilities, backup communications

Step four is to implement the plan, which involves integrating emergency planning into the operation of the mine and mill. The plan should be reviewed at regular intervals and after any event at any similar facility for lessons learned that could be applied. Training and exercising with off-site responders will allow them to be comfortable responding to emergencies at the facility.

In Canada, because there is consistency of regulatory authority in the regulation of uranium mining, processing, reclamation, and long-term stewardship, emergency planning for uranium mines and mills is summarized in a single regulatory guide. The guidance is in general agreement with the U.S. FEMA guidance, but is more specific about radiation exposure, limiting the spread of radioactive contamination, postaccident monitoring for radioactive contamination, and maintaining the security of radioactive materials.

[a]See http://www.fema.gov/business/guide/section1a.shtm; accessed September 2011.

regulatory standards. In addition, a culture in which worker and public health, protection of environmental resources, and preservation of ecological resources

reasonable effort to maintain exposures to radiation as far below the dose limits . . . as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest" (10 CFR § 20.1003).

BOX 8.3
Best Practices in Closure and PostClosure

When a uranium mining or processing site reaches the end of its active operation, the ultimate goal is to ensure that the site will be safe and ecologically healthy indefinitely into the future. Hazards may include nonradiological as well as radiological hazards to workers, members of the public, and the environment; both types of hazards should be addressed during decommissioning (IAEA, 2006b). Decommissioning activities for a uranium mine may include, for example, capping shafts, removing chemicals and fuels from the site, filling and contouring water treatment ponds, removing structures, revegetating, and restoring normal water flow (IAEA, 1998). Postclosure stewardship activities also will be required. These activities may include, for example, ongoing monitoring, collecting and treating contaminated water, managing and storing water treatment sludges, and maintaining covers, water diversion structures, etc. (see IAEA, 2010). Decommissioning and subsequent stewardship activities should be done within the context of a site-specific closure plan.

Three broad principles should guide closure planning for uranium processing or mining sites:

- Closure planning should be anticipatory.
- Closure planning should be iterative and adaptable.
- Closure planning should recognize the need for and limits of long-term stewardship.

Closure planning should be anticipatory. According to the IAEA (1998), closure plans should be developed for prospective uranium mining projects *before* a project proceeds. Decommissioning principles should be identified: for example, the maximum acceptable effective dose to any person at any time, the use of state-of-the-art engineering practices even if analyses suggest that lesser efforts may be sufficient. The plan should be prepared by the facility operator and discussed with and approved by the regulatory agencies (IAEA, 1998). Similarly, early consideration of stewardship issues and preparation for a stewardship program is important: According to the IAEA (2006a), stewardship plans typically are required as part of the licensing procedure for a new operation.

Closure planning should be iterative and adaptable. A closure plan developed at the time of permit application is, in effect, an interim plan that is based on forecasts and projections. The plan for closure and decommissioning should be reevaluated periodically as the operation goes on (IAEA, 1998). Similarly, a postclosure stewardship program needs to be capable of responding and adapting to changes in societal and governance structures, stakeholders and perceptions of risk, economic circumstances, and state-of-the-art science and technology (IAEA, 2006a). Allowance also should be made for the possible need for emergency interventions—that is, actions taken to avert or reduce exposure to radiological and nonradiological risks as a consequence of an accident or uncontrolled practice (IAEA, 2006b).

Closure planning should recognize the need for and limits of long-term stewardship. Within the context of sites with long-term radiological and non-radiological hazards, stewardship in its broadest sense includes all of the activities required to manage any potentially harmful residual contamination left on-site after a facility has stopped operating and its site has been remediated (NRC, 2000). These activities may include the following:

- Measures to maintain isolation of residual contamination
- Measures to monitor the migration and attenuation or evolution of residual contamination
- Restrictions on land use and site access
- Conducting oversight and, if needed, enforcement
- Gathering, storing, and retrieving information about residual contaminants and other conditions on-site, as well as about changes in relevant off-site conditions
- Disseminating information about the site, including any use restrictions
- Periodically evaluating how well the protective system is working
- Evaluating new technological options to eliminate, reduce, prevent the migration of, or monitor residual contaminants (NRC, 2000)

Long-term stewardship of residually contaminated sites also has been described as entailing the following roles (NRC, 2003, p. 2, emphasis in the original):

- A *guardian*, stopping activities that could be dangerous
- A *watchman* for problems as they arise, via monitoring that is effective in design and practice, activating responses and notifying responsible parties as needed
- A *land manager*, facilitating ecological processes and human use
- A *repairer* of engineered and ecological structures as failures occur and are discovered, as unexpected problems are found, and as re-remediation is needed
- An *archivist* of knowledge and data, to inform the future
- An *educator* to affected communities, renewing memory of the site's history, hazards, and burdens
- A *trustee*, assuring the financial wherewithal to accomplish all of the other functions

Together with this broad spectrum of activities and roles, effective stewardship programs appear to have a common set of attributes: long-term reliability; clarity of objectives and roles; adequate and dependable funding; ease of implementation; transparency; flexibility, iterativity, adaptability, and the ability to deal with contingencies; durability or replaceability; and means to incorporate scientific, technical, and societal changes (IAEA, 2006a).

The nature and duration of the necessary activities and roles will depend on the nature and duration of the residual contamination. It is quite possible, however, that the duration of risks from residual contamination will exceed the institutional capacity to reliably perform stewardship activities. It is widely recognized that

continued

BOX 8.3 Continued

predicting how economic, social, and institutional systems will evolve is fraught with uncertainty—uncertainty that grows larger as the time frame grows longer (NRC, 2000, 2003; Falck, 2008; IAEA, 2006a). A major challenge for a successful stewardship program is to reduce the risks arising from this uncertainty (IAEA, 2006a).

One suggestion is to focus the stewardship program on a realistic time frame, such as 100 years, and on short-term solutions that will keep people involved in the site while allowing for evaluation of changes needed over time (IAEA, 2006a). A complementary decision-aiding tool is to rate the risks of the site if active control of its residual contamination were to break down in the future (Falck, 2008). In addition, defining the stewardship program from the bottom up, at the practical level of implementation, is essential (IAEA, 2006a).

are highly valued, and continuously assessed and strengthened, is the ultimate goal of a regulatory program. To encourage and facilitate best management practices and social responsibility commitments to local communities, it is necessary to take advantage of continual improvement in technologies and develop performance-based and risk-informed regulations and policies. In the event that the uranium mining moratorium is lifted, the statutes and regulations that enable the development of a mining and/or processing facility would ideally be written to ensure minimal permanent impact on the environment and protect public health. Such statutes and regulations would encompass the following points:

- ***Ensure that life-cycle costs as well as long-term stewardship needs are reflected in the type of, and amount of, the financial surety.*** Financial security needs are set at the level necessary to maintain the integrity of the integrated system so that the system is a sustainable enterprise. Cost estimates need to be reviewed and updated throughout the life cycle of the project to ensure that they accurately reflect the costs and resources that are needed. The burden is on the facility to demonstrate that the amount of the financial surety is sufficient. Instruments to demonstrate financial surety should have the flexibility to be applied in temporary shutdown conditions as well as planned closure. In the event that remediation is necessary and complete cleanup is not possible, the facility would have to demonstrate financial capability to proceed with remediation as well as having resources dedicated to long-term stewardship activities.
- ***Ensure that inspection and enforcement tools are transparent, practical, sufficient, available, independent, and sustainable.*** "Transparency" requires that the enforcement tools be clear and comprehensible to the regulated community, the public, and the regulator; "practical" requires that the enforcement tools be

easily implemented; "sufficient" means that the enforcement tools are effective in producing deterrence; "available" means that regulatory agencies should have available adequate funding and other resources to function in an environment of continuous improvement to enable them to take full advantage of international uranium mining and processing innovations; "independent" means that the regulatory agency would provide independent verification of compliance and not be overly influenced by the industry that it is regulating, even if the funding for the regulatory agency is derived from a fee placed on the industry; and "sustainable" requires that enforcement actions be supported by strong scientific and other evidence that will meet legal standards.

- In the event that the uranium mining moratorium is lifted, Virginia will be required to establish a regulatory program for uranium mining. It might also establish a regulatory program for uranium processing and reclamation. ***Development of this new regulatory structure could theoretically be based on existing laws, but the optimum approach would be for an entirely new uranium mining, processing, and reclamation law or laws to be enacted. In addition, a new regulatory program would be required to implement this law or laws.***
- In the event that Virginia decides to lift its uranium mining moratorium, it is possible that regulatory authority could be distributed among several agencies. ***If this is the case, effective interagency integration and coordination will be imperative. Interagency integration and coordination will require more than co-location in the same facility; it will require commitment and leadership by the legislative and executive branches of the government, and it will also require that sufficient resources be available for developing and fine-tuning a regulatory program.***
- The committee recognizes that the federal regulations governing uranium processing are currently under consideration for revision by the USNRC. Additionally, the USEPA is reviewing and potentially revising its health and environmental standards for uranium processing facilities. ***Virginia should be actively involved in the regulatory processes of these federal agencies to ensure good federal–state coordination. The international community has considerable knowledge of regulating uranium mines and mills and can offer additional insight into regulatory best practices.***
- At present, the laws applicable in Virginia do not require that an environmental impact assessment be undertaken before hard-rock mining operations commence. ***Modern best international practice requires an environmental impact assessment prior to the commencement of any mining activities.***

OVERARCHING CONCLUSION

The committee's charge was to provide information and advice to the Virginia legislature as it weighs the factors involved in deciding whether to allow uranium mining. This report describes a range of potential issues that could arise if the

moratorium on uranium mining were to be lifted, as well as providing information about best practices—applicable over the full uranium extraction life cycle—that are available to mitigate these potential issues.

If the Commonwealth of Virginia rescinds the existing moratorium on uranium mining, there are steep hurdles to be surmounted before mining and/or processing could be established within a regulatory environment that is appropriately protective of the health and safety of workers, the public, and the environment. There is only limited experience with modern underground and open-pit uranium mining and processing practices in the wider United States, and no such experience in Virginia. At the same time, there exist internationally accepted best practices, founded on principles of openness, transparency, and public involvement in oversight and decision making, that could provide a starting point for the Commonwealth of Virginia were it to decide that the moratorium should be lifted. After extensive scientific and technical briefings, substantial public input, reviewing numerous documents, and extensive deliberations, the committee is convinced that the adoption and rigorous implementation of such practices would be necessary if uranium mining, processing, and reclamation were to be undertaken in the Commonwealth of Virginia.

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Glossary

ALARA. As low as (is) reasonably achievable.

Alluvial. A general term for clay, silt, sand, gravel, or similar unconsolidated detrital material, deposited during comparatively recent geological time by a stream or other body of running water.

Alpha (α) decay. *Radioactive decay* in which an *alpha particle* (*nucleus* of the ^{4}He atom, consisting of two protons and two neutrons) is emitted.

Anatexis. The partial melting of preexisting rock. It implies in situ partial melting.

Anticline. A fold, generally convex upward, whose core contains the stratigraphically older rocks.

Aquifer. A body of rock that contains sufficient saturated permeable material to conduct groundwater and to yield significant quantities of water to wells and springs.

Aureole. A zone surrounding an igneous intrusion in which the country rock shows the effects of *contact metamorphism.*

Backfill. Waste rock or aggregate used to support the roof or walls of a mine after removal of ore.

Basalt. A general term for dark-colored mafic igneous rocks, commonly extrusive but locally intrusive (e.g., as dikes), composed chiefly of calcic plagioclase and clinopyroxene; the fine-grained equivalent of *gabbro*.

Basement. The crust of the Earth below sedimentary deposits, extending downward to the Mohorovicic discontinuity. In many places the rocks of the complex are igneous and metamorphic and of Precambrian age, but in some places they are Paleozoic, Mesozoic, or even Cenozoic.

Bench. The horizontal step or floor along which coal, ore, stone, or overburden is worked or quarried.

Beta (β) decay. *Nuclear decay* in which a *β particle* (an electron ejected from a *radioactive nucleus*) is emitted or in which orbital *electron capture* occurs.

Breccia. A coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix; it differs from *conglomerate* in that the fragments have sharp edges and unworn corners.

Calcrete. A term for a pedogenic calcareous soil, for example, limestone consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution and redeposited through the agency of infiltrating waters.

Caldera. A large, basin-shaped volcanic depression, more or less circular or cirquelike in form, formed by collapse during an eruption.

Carbonate. Sediments or rocks formed by the biotic or abiotic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron, for example, limestone and dolomite. Aqueous carbonate species include CO_2, H_2CO_3, and the HCO_3^- and CO_3^{2-} ions.

Cataclasite. A fine-grained, cohesive rock with angular fragments that have been produced by the crushing and fracturing of preexisting rocks as a result of mechanical forces in the crust, normally lacking a penetrative foliation or microfabric.

Cohort. A group of individuals having a statistical factor (such as age or risk) in common.

Compaction. Any process, such as burial or desiccation, by which a soil mass loses pore space and becomes denser; or the densification of a soil by mechanical means, accomplished by rolling, tamping, or vibrating, usually at controlled water content.

Conglomerate. A coarse-grained clastic sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter (granules, pebbles, cobbles, boulders) typically containing fine-grained particles (sand, silt, clay) in the interstices, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay.

Dewatering. The removal of water from a drowned shaft or waterlogged workings by pumping or drainage as a safety measure or as a preliminary step to resumption of development in the area.

Diagenesis. The sum of all chemical and physical changes in minerals during and after their initial accumulation, a process limited on the high-temperature, high-pressure side by the lowest grade of metamorphism.

Dike. A tabular igneous intrusion that cuts across the bedding or foliation of the country rock.

Dissolved load. The part of the total *stream load* that is carried in solution, such as chemical ions yielded by erosion of the landmass during the return of rainwater to the ocean.

Dose-response. Of, relating to, or graphing the pattern of physiological response to varied dosage (as of a drug or radiation) in which there is typically little or no effect at very low dosages and a toxic or unchanging effect at high dosages with the maximum increase in effect somewhere between the extremes.

Drift. A horizontal opening in or near an orebody and parallel to the course of the vein or the long dimension of the orebody.

Effluent. A liquid discharged as waste, such as contaminated water from a factory or the outflow from a sewage works; water discharged from a storm sewer or from land after irrigation.

E_h (redox potential). Measures the tendency of a *chemical species* to acquire *electrons* and be *reduced*. Reduction/*oxidation* potential of a compound is measured under standards conditions against a standard reference half-cell. In biological systems, the standard redox potential is defined at pH 7.0 versus the hydrogen electrode and *partial pressure* of hydrogen = 1 *bar*.

Epithelium. A membranous cellular tissue that covers a free surface or lines a tube or cavity of an animal body and serves especially to enclose and protect the other parts of the body, to produce secretions and excretions, and to function in assimilation.

Equilibrium factor. The ratio of decay products to radon.

Equivalent dose. An absorbed dose that is averaged over an organ or tissue and weighted for the radiation quality.

Erosion. The general process or the group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another, by natural agencies, which include weathering, solution, corrasion, and transportation, but usually exclude mass wasting; specifically the mechanical destruction of the land and the removal of material (such as soil) by running water (including rainfall), waves and currents, moving ice, or wind.

Exposure. The condition of being subject to some detrimental effect or harmful condition.

Exposure pathway. The route a substance takes from its source (where it began) to its end point (where it ends), and how people can come into contact with (or get exposed to) it. An exposure pathway has five parts: a source of contamination, an *environmental medium and transport mechanism*, a *point of exposure*, a *route of exposure*, and a *receptor population*.

Felsic. A mnemonic adjective applied to an igneous rock having abundant light-colored minerals in its mode; also, applied to those minerals (quartz, feldspars, feldspathoids, muscovite) as a group.

Fluvial. Produced by the action of a stream or river.

Fractional crystallization. A differentiation process whereby previously formed crystals are physically separated from the magma and thus prevented from equilibrating with the liquid from which they grew, resulting in a series of residual liquids of more extreme compositions than would have resulted from equilibrium crystallization.

French drain. A covered ditch containing a layer of fitted or loose stone or other pervious material.

Gamma (γ) radiation. Electromagnetic *radiation* emitted in the process of *nuclear transformation* or particle *annihilation*.

Gangue. The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration.

Geochronometer. A physical feature, material, or element whose formation, alteration, or destruction can be calibrated or related to a known interval of time.

Grade. The classification of an ore according to the desired or worthless material in it or according to value.

Granite. A plutonic rock in which quartz constitutes 10 to 50 percent of the felsic components and in which the alkali feldspar/total feldspar ratio is generally restricted to the range of 65 to 90 percent.

Gray. The *SI* unit of *absorbed radiation dose* of *ionizing radiation*, defined as the absorption of one *joule* of *ionizing radiation* by one *kilogram* of *matter*. 1 Gy is equal to 100 rads.

Ground control. Maintaining rock mass stability by controlling the movement of excavations in the ground, which can be either rock or soil.

Groundwater. That part of the subsurface water that is in the *saturated zone*, including underground streams. Loosely, all *subsurface water* as distinct from surface water.

Hardness. A property of water causing formation of an insoluble residue, primarily due to the presence of ions of calcium and magnesium, but also to ions of other alkali metals, other metals (e.g., iron), and even hydrogen. Hardness of water is generally expressed as parts per million as $CaCO_3$.

Healthy worker effect. Phenomenon of workers usually exhibiting overall death rates lower than those of the general population due to the fact that the severely ill and disabled are ordinarily excluded from employment.

Hematite. A common iron mineral: Fe_2O_3. Hematite occurs in splendent, metallic-looking, steel-gray or iron-black rhombohedral crystals, in reniform masses or fibrous aggregates, or in deep-red or red-brown earthy forms. It is found in igneous, sedimentary, and metamorphic rocks and is the principal ore of iron.

Hydrology. The science that deals with water (both liquid and solid), its properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere, from the moment of its precipitation until it is returned to the atmosphere through evapotranspiration or is discharged into the ocean.

In situ leaching/ in situ recovery (ISL/ISR). A hydrometallurgical process that treats ore for the recovery of minerals while the ore is in place underground. It is a mineral recovery technique where no mine waste piles or tailings impoundments are created.

Intercalated. Said of layered material that exists or is introduced between layers of a different character; especially said of relatively thin strata of one kind of material that alternate with thicker strata of some other kind, such as beds of shale that are intercalated in a body of sandstone.

Ionizing radiation. Any radiation consisting of directly or indirectly ionizing particles or a mixture of both, or photons with energy higher than the energy of photons of ultraviolet light or a mixture of both such particles and photons.

Isotope. One of two or more species of the same chemical element, that is, having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. The isotopes of an element have slightly different physical and chemical properties, owing to their mass differences, by which they can be separated.

Karst. A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by *dissolution.* It is characterized by *sinkholes, caves,* and underground drainage.

Leaching. Metallurgical process for dissolution of metals by means of an acid or alkaline solution.

Lenticular. Resembling in shape the cross section of a lens, especially of a double-convex lens.

Lining. A layer of clay, concrete, synthetic film, or other material, placed under or over all or part of the perimeter of a conduit, reservoir, or landfill to resist erosion, minimize seepage losses or the escape of gases, withstand pressure, and improve flow.

Lithology. The description of rocks, especially in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition, and grain size.

Load. The material that is moved or carried by a natural transporting agent, such as a stream, a glacier, the wind, or waves, tides, and currents; or the quantity or amount of such material at any given time.

Mafic. Said of an igneous rock composed chiefly of one or more ferromagnesian, *dark-colored* minerals in its mode; also, said of those minerals.

Matrix. The finer-grained material enclosing, or filling the interstices between, the larger grains or particles of a sediment or sedimentary rock; the natural material in which a sedimentary particle is embedded.

Maximum contaminant level (MCL). The maximum permissable level of a contaminant in water which is delivered to any user of a public water system.

Meta-analysis. A method that takes results of two or more studies of the same research question and combines them into a single analysis. The purpose of meta-analysis is to gain greater accuracy and statistical power by taking advantage of the large sample size resulting from the cumulation of results over multiple studies. Meta-analysis typically uses the summary statistics from the individual studies, without requiring access to the full dataset. Key components of meta-analysis include ensuring the availability of a common metric across all studies and the use of appropriate algorithms for combining or averaging those metrics across studies and assessing statistical significance.

Metaluminous. Said of an igneous rock in which the molecular proportion of aluminum oxide is greater than that of sodium and potassium oxides combined but generally less than of sodium, potassium, and calcium oxides combined.

Metamorphism. The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions that have generally been imposed at depth, below the surface zones of weathering and cementation, and differ from the conditions under which the rocks in question originated.

Metasomatism. The open-system metamorphic process in which the original chemical composition of a rock is changed by reaction with an external source. The process is commonly thought to occur in the presence of a fluid medium flowing through the rock. Metasomatism may also occur by grain-boundary diffusion or by diffusion through a static fluid medium.

Mylonite. A fine-grained, foliated rock, commonly with poor fissility and possessing a distinct lineation.

Nepheline syenite. A plutonic rock composed essentially of alkali feldspar and nepheline. It may contain an alkali ferromagnesian mineral, for example, an amphibole or a pyroxene.

Nephrotoxicity. Resulting from or marked by poisoning of the kidney.

Ore. The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably or to satisfy social or political objectives.

Overburden. Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials, ores, or coal, especially those deposits that are mined from the surface by open cuts.

Oxidation. The complete, net removal of one or more electrons from a *molecular entity*.

Peralkaline. Said of an igneous rock in which the molecular proportion of aluminum oxide is less than that of sodium and potassium oxides combined.

Peraluminous. Said of an igneous rock in which the molecular proportion of aluminum oxide is greater than that of sodium and potassium oxides combined.

Permeability. The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure and is a function only of the medium.

Permissible exposure limits. Regulatory limits on the amount or concentration of a substance in the air, designed to protect workers against the health effects of exposure to hazardous substances.

Phosphorite. A sedimentary rock with a high enough content of phosphate minerals to be of economic interest. Most commonly it is a bedded primary or reworked secondary marine rock composed of microcrystalline carbonate fluorapatite in the form of laminae, pellets, oolites, nodules, and skeletal, shell, and bone fragments.

Pooled analysis. A method of analysis that combines primary data from several studies and then conducts analysis on the enlarged data set.

Porphyry copper deposit. A large body of rock, typically porphyry, that contains disseminated chalcopyrite and other sulfide minerals. Such deposits are mined in bulk on a large scale, generally in open-pits, for copper and byproduct molybdenum. Most deposits are 3 to 8 km across, and of low grade (less than 1% Cu).

Pregnant solution. A concentrated, purified uranium solution.

Protore. In older writings, any primary mineralized material too low in tenor to constitute ore but from which ore may be formed through secondary enrichment. As commonly employed today, the rock below the sulfide zone of supergene enrichment; the primary material that cannot be produced at a profit under existing conditions but that may become profitable with technological advances or price increases.

Rad. A unit of absorbed *radiation* dose causing 0.01 *joule* of *energy* to be absorbed per *kilogram* of *matter*. It is equal to 1 centiGray (cGy).

Radioactive decay. *Nuclear decay* in which particles or electromagnetic *radiation* are emitted or the *nucleus* undergoes *spontaneous fission* or *electron capture*.

Radioactivity. The property of certain nuclides showing radioactive decay.

Radionuclide. A *nuclide* (species of atom) that is *radioactive*.

Radon progeny. The short-lived decay products of radon, an inert gas that is one of the natural decay products of uranium. The short-lived radon progeny (i.e., polonium-210, lead-214, bismuth-214, and polonium-214) are solids and exist in air as free ions or as ions attached to dust particles.

Raffinate. The aqueous solution remaining after the metal has been extracted by the solvent; the tailing of the solvent extraction system.

Reagent. A substance that is consumed in the course of a chemical reaction.

Recommended exposure limit. An *occupational exposure limit* recommended by the U.S. *National Institute for Occupational Safety and Health* as being protective of worker safety and health over a working lifetime if used in combination with engineering and work practice controls, exposure and medical monitoring, posting and labeling of hazards, worker training, and *personal protective equipment*.

Reduction. The complete transfer of one or more electrons to a *molecular entity*.

Rem. The "Roentgen equivalent in man," a unit of radiation dose equivalent that is the product of absorbed radiation (rads) and a weighting factor. It is equal to 1 centiSievert (cSv).

Runoff. That part of precipitation appearing in surface streams. It is more restricted than *streamflow,* because it does not include stream channels affected by artificial diversions, storage, or other human works.

Sandstone. A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size with or without a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent of sand, intermediate in texture between conglomerate and shale.

Sediment. Solid fragmental material that originates from weathering of rocks and is transported or deposited by air, water, or ice, or that accumulates by other natural agents, such as chemical precipitation from solution or secretion by organisms, and that forms in layers on the Earth's surface at ordinary temperatures in a loose, unconsolidated form, for example, sand, gravel, silt, mud, till, loess, alluvium.

Sievert. The SI unit for dose equivalent, which is the absorbed dose of ionizing radiation weighted with other factors. It is measured in J/kg.

Silica. Silicon dioxide (SiO_2), which occurs naturally in crystalline, amorphous, and impure forms (as in quartz, opal, and sand, respectively).

Siliciclastic. Pertaining to clastic noncarbonate rocks which are almost exclusively silicon-bearing, either as forms of quartz or as silicates.

Silicosis. Pneumoconiosis characterized by massive fibrosis of the lungs resulting in shortness of breath and caused by prolonged inhalation of silica dusts.

Shotcrete. A mixture of portland cement, sand (commonly including coarse aggregate), and water applied by pneumatic pressure through a specially adapted hose and used as a fireproofing agent and as a sealing agent to prevent weathering of mine timbers and roadways.

Skarn. An old Swedish mining term for silicate gangue (amphibole, pyroxene, garnet, etc.) of certain iron-ore and sulfide deposits of Archean age, particularly those that have replaced limestone and dolomite.

Stoping. Extraction of ore in an underground mine by working laterally in a series of levels or steps in the plane of a vein. It is generally done from lower to upper levels, so that the whole vein is ultimately removed. The process is distinct from working in a shaft or tunnel or in a room in a horizontal drift, although the term is used in a general sense to mean the extraction of ore.

Stratiform. Having the form of a layer, bed, or stratum; consisting of roughly parallel bands or sheets.

Sulfate. A mineral compound characterized by the sulfate radical SO_4. Anhydrous sulfates, such as barite, $BaSO_4$, have divalent cations linked to the sulfate radical; hydrous and basic sulfates, such as gypsum, $CaSO_4 \cdot 2H_2O$, contain water molecules.

Sulfide. A mineral compound characterized by the linkage of sulfur with a metal or semimetal, such as galena (PbS) or pyrite (FeS_2).

Suspended load. The part of the total *sediment load* that is carried for a considerable period of time in suspension, free from contact with the bed; it consists mainly of clay, silt, and sand.

Tailings. The gangue and other refuse material resulting from the washing, concentration, or treatment of ground ore.

Tectonics. A branch of geology dealing with the broad architecture of the outer part of the Earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origin, and historical evolution.

Tuberculosis. A usually chronic, highly variable disease that is caused by a bacterium of the genus *Mycobacterium* (*M. tuberculosis*), is usually communicated by inhalation of the airborne causative agent, affects especially the lungs but may spread to other areas from local lesions or by way of the lymph or blood vessels, and is characterized by fever, cough, difficulty in breathing, inflammatory infiltrations, formation of tubercles, caseation, pleural effusion, and fibrosis.

Unconformity. The structural relationship between rock strata in contact, characterized by a lack of continuity in deposition, and corresponding to a period of nondeposition, weathering, or especially erosion (either subaerial or subaqueous) prior to the deposition of the younger beds, and often (but not always) marked by absence of parallelism between the strata.

Vein. An epigenetic mineral filling of a fault or other fracture in a host rock, in tabular or sheetlike form, often with associated replacement of the host rock; a mineral deposit of this form and origin.

Water table. The surface between the zone of saturation and the zone of aeration; that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Watershed. The region drained by, or contributing water to, a stream, lake, or other body of water.

Waste rock. Barren or submarginal rock or ore that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of the milling processes.

Working level. Any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha particle energy.

Working level month. An exposure to 1 working level for 170 hours (2,000 working hours per year/12 months per year = approximately 170 hours per month).

Yellowcake. Concentrated, high-purity (75-85%) uranium oxide (U_3O_8), which is used as the raw material for nuclear fuel fabrication.

Appendix A

Study Request Letters

The letter received from Delegate Kilgore, on behalf of the Virginia Coal and Energy Commission, requesting that the National Research Council undertake a study to assess whether uranium could be mined and processed safely in the Commonwealth of Virginia is appended below. Letters supporting the study request from U.S. Senators Mark Warner and Jim Webb and from Governor Kaine are also appended.

TERRY G. KILGORE
P.O. BOX 669
GATE CITY, VA 24251

FIRST DISTRICT
(Lee, Scott & Portions of
Wise and Washington Counties)

COMMONWEALTH OF VIRGINIA
HOUSE OF DELEGATES
RICHMOND

(276) 386-7701
FAX: (276) 386-2377
Richmond: (804) 698-1001
E-Mail Address: delegate@mounet.com
www.terrykilgore.net

COMMITTEE ASSIGNMENTS:
COURTS OF JUSTICE
COMMERCE AND LABOR
MILITIA, POLICE AND PUBLIC SAFETY
RULES

August 20, 2009

Dr. E. William Colglazier
Executive Officer, Chief Operating Officer
National Research Council
500 Fifth Street, NW
Washington, DC 20001

Re: Virginia Coal and Energy Commission--Request for Uranium Study

Dear Dr. Colglazier:

As Chair of the Coal and Energy Commission, established in the legislative branch of state government pursuant to Chapter 25 of Title 30 of the Code of Virginia, I write to formally request that the National Research Council ("NRC") undertake a study of whether uranium can be mined and milled safely in the Commonwealth of Virginia. I understand that informal discussions have occurred about this assignment between NRC and Dr. Michael E. Karmis, Director of the Virginia Center for Coal and Energy Research at Virginia Tech.

The Commission believes that such a study is critical for a number of reasons: our country's concern about energy independence and clean energy; the location in the Commonwealth of the largest known untapped uranium ore body in North America consisting of an estimated 120 million pounds of uranium in Pittsylvania County, located in south central Virginia; and the potential that this discovery of uranium offers for greater economic development opportunities in a predominantly rural area of the state as well as for nuclear energy-related research.

The Coal and Energy Commission was established by the Virginia General Assembly in 1979. It consists of 20 members, thirteen of whom serve as members of the House of Delegates or the Senate of Virginia. The seven non-legislative citizen members are appointed by the Governor. Among its statutory responsibilities, the Commission endeavors to "stimulate, encourage, promote, and assist in the development of renewable and alternative energy resources other than petroleum." We serve in an advisory capacity to the Governor and executive branch agencies upon energy-related matters, we encourage research designed to further new and more extensive use of the coal as well as alternative and renewable energy resources of the Commonwealth, and we make recommendations, from time to time, to the Governor and General Assembly on our own initiative. (*see* Section 30-189, Code of Virginia, 1950, as amended).

NOT PAID FOR AT GOVERNMENT EXPENSE

In view of the large uranium ore body in the Commonwealth, the Commission agreed last year to consider whether uranium is a resource that should be developed as part of the Commonwealth's energy portfolio. Toward that end, I appointed a committee of the Commission to investigate the issue, to define a scope of study, contract with such third parties as appropriate to conduct the study and report its findings to the Commission. Delegate Lee Ware chairs that committee.

After extensive public hearings over the course of six months and input from a number of interested parties, Delegate Ware's committee adopted a scope of study or "statement of task" on May 21, 2009, a copy of which is enclosed.

I understand that Dr. Karmis, who has worked with Delegate Ware's committee, has also had preliminary discussions with Dr. Warren Muir, Executive Director of the Division on Earth and Life Studies, Dr. Anthony R. de Souza, Director of the Board on Earth Sciences and Resources ("BESR") and Dr. Elizabeth A. Eide, Staff Officer with BESR, and that the parties have an understanding of how best to proceed in undertaking this assignment. Dr. Karmis worked closely with the committee in developing the statement of task which sets forth the elements of the study.

I write to request that the NRC work with the Virginia Center for Coal and Energy Research as the sponsor of the project. We hope that the questions asked in the enclosed statement of task will serve as the basis for your work. We do not know what would constitute a reasonable length of time to examine the issues set forth in the statement and will be interested in your assessment in that regard.

As for funding, after our solicitation to all interested parties, we have received a firm commitment to underwrite the costs of the study. Those funds can be transferred to the Virginia Center for Coal and Energy Research when the statement of task and an agreement have been reached with the NRC.

We look forward to hearing from you.

Thank you.

Sincerely yours,

Terry G. Kilgore

Del. Kilgore

Enclosure

cc: Dr. Warren Muir, Executive Director, Division on Earth and Life Studies
Dr. Anthony R. de Souza, Director, Board on Earth Sciences and Resources
Dr. Elizabeth A. Eide, Senior Program Officer, Board on Earth Sciences and Resources

Dr. Michael E. Karmis, Director of the Virginia Center for Coal and Energy Research
The Honorable Timothy G. Kaine, Governor of the Commonwealth of Virginia
The Honorable L. Preston Bryant, Jr., Secretary of Natural Resources, Commonwealth of Virginia
The Honorable John C. Watkins, Vice Chair, Virginia Coal and Energy Commission
The Honorable R. Lee Ware, Chair, Uranium Study Committee of the Virginia Coal and Energy Commission
Ellen Porter, Division of Legislative Service

MARK R. WARNER
VIRGINIA

COMMITTEES:
BANKING, HOUSING, AND URBAN AFFAIRS
COMMERCE, SCIENCE, AND TRANSPORTATION
BUDGET
RULES AND ADMINISTRATION

United States Senate
WASHINGTON, DC 20510–4606

September 18, 2009

RECEIVED
National Research Council
Executive Office

Dr. E. William Colglazier
Executive Officer, Chief Operating Officer
National Research Council
500 Fifth Street, NW
Washington, DC 20001

Dear Dr. Colglazier:

I want to inform you of an opportunity in Virginia that could help provide a potential solution to our nation's energy needs. I understand that the Virginia Coal and Energy Commission has formally requested the National Research Council ("NRC"), as the operating arm of the National Academy of Science, to undertake a study to review the scientific, technical and regulatory aspects of uranium mining, milling and processing and to assess environmental and human health and safety issues as they relate to the Commonwealth and specifically Pittsylvania County. The request arises from the discovery of a large uranium ore body in Pittsylvania County, Virginia, known as the "Coles Hill Deposit".

Two years ago the Commonwealth adopted the "Virginia Energy Plan" which has the potential to promote the Commonwealth's energy independence and to educate consumers on energy conservation and efficiency. As a nation, we should consider the whole portfolio approach to energy, and consider all possible resources as we attempt to confront our energy needs and work to reduce our dependence on foreign sources of energy.

While recognizing the tremendous potential economic benefits from mining uranium, I think it is critical that the environmental and health impacts from uranium mining be carefully examined. Because of the pre-eminent, international reputation of the National Research Council of the National Academy of Sciences, I can think of no entity more qualified to meet the challenge of addressing the important issues requested for study by the Virginia Coal and Energy Commission, and I hope that you will consider my request.

Sincerely,

Mark R Warner

MARK R. WARNER
United States Senator

http://warner.senate.gov
PRINTED ON RECYCLED PAPER

JIM WEBB
VIRGINIA

COMMITTEE ON
ARMED SERVICES
COMMITTEE ON
FOREIGN RELATIONS
COMMITTEE ON
VETERANS' AFFAIRS
JOINT ECONOMIC COMMITTEE

WASHINGTON OFFICE:
WASHINGTON, DC 20510
(202) 224-4024

United States Senate
WASHINGTON, DC 20510-4605

October 19, 2009

Ralph J. Cicerone
President of the National Academy of Sciences
500 Fifth Street, NW
Washington, DC 20001

Dear Dr. Cicerone:

As you are aware, the Virginia Coal and Energy Commission has requested the National Academy of Science undertake a study to examine uranium mining in the Commonwealth of Virginia. According to the Commission, the study would examine the scientific, technical, environmental, human health and safety, and regulatory aspects of uranium mining, milling, and processing. The request arises from the discovery of a large uranium deposit in Pittsylvania County, Virginia.

It is my understanding that the Academy is considering whether to undertake this request. Uranium resources will continue to play a critical role in the nation's energy security. Recovering the Pittsylvania County deposit, however, hinges on the ability to fully protect human health and the environment. The National Academy is well qualified to provide the federal government and the public with unbiased, objective advice on this issue.

While recognizing the tremendous economic and energy security benefits from mining uranium, I would like to urge the Academy to fully examine any environmental and health impact associated with this activity. I am confident that the Academy will conduct this study free from bias and with the best available science, consistent with the long established traditions of the institution.

Thank you for considering this request.

Sincerely,

Jim Webb

Jim Webb
United States Senator

COMMONWEALTH of VIRGINIA

Office of the Governor

Timothy M. Kaine
Governor

November 6, 2009

Dr. E. William Colglazier
Executive Officer, Chief Operating Officer
National Research Council
500 Fifth Street, NW
Washington, DC 20001

Dear Dr. Colglazier:

I understand that the Virginia Coal and Energy Commission has formally requested the National Research Council ("NRC"), as the operating arm of the National Academy of Science, to undertake a study to review the scientific, technical and regulatory aspects of uranium mining, milling and processing and to carefully assess environmental and human health and safety issues as they relate to the Commonwealth and specifically Pittsylvania County.

Two years ago I announced the Virginia Energy Plan, a proposal to promote the Commonwealth's energy independence and to educate consumers on energy conservation and efficiency. The Plan was required by the 2006 General Assembly and was prepared by a broad-based advisory group.

Among many other provisions of the Plan is a recommendation that "Virginia should assess the potential value of and regulatory needs for uranium production in Pittsylvania County." [page 28, Virginia Energy Plan.] Recognizing the need to fuel Virginia's nuclear power plants, the Plan further states that "the potential to mine Virginia uranium is therefore strategically important and warrants careful analysis." [page 42, Virginia Energy Plan.]

Patrick Henry Building • 1111 East Broad Street • Richmond, Virginia 23219
(804) 786-2211 • TTY (800) 828-1120
www.governor.virginia.gov

Dr. E. William Colglazier
November 6, 2009
Page 2

Because of the pre-eminent, international reputation of the National Research Council of the National Academy of Sciences, I can think of no entity more qualified to meet the challenge of assessing the potential risks and benefits of mining uranium in Pittsylvania County, and determining whether it is possible to do so in a safe, environmentally responsible way.

Sincerely,

Timothy M. Kaine

c: The Honorable Terry G. Kilgore, Chair, Coal and Energy Commission
The Honorable John C. Watkins, Vice Chair, Virginia Coal and Energy Commission
The Honorable R. Lee Ware, Chair, Uranium Study Committee of the Virginia Coal and Energy Commission
The Honorable L. Preston Bryant, Jr., Secretary of Natural Resources, Commonwealth of Virginia
Mr. Stephen A. Walz, Director, Department of Mines, Minerals and Energy, Commonwealth of Virginia

Appendix B

Committee Biographical Sketches

Paul A. Locke *(Chair),* an environmental health scientist and attorney, is an associate professor at the Johns Hopkins University Bloomberg School of Public Health in the Department of Environmental Health Sciences, Division of Toxicology. He holds an M.P.H. from Yale University School of Medicine, a Dr.P.H. from the Johns Hopkins University Bloomberg School of Public Health, and a J.D. degree from Vanderbilt University School of Law. Dr. Locke's research and practice focus on how decision makers use environmental health science and toxicology in regulation and policy making and how environmental health sciences influence the policy-making process. His areas of study include designing and evaluating radiation protection initiatives and radiation policies, especially in the areas of low-dose radiation science, radon risk reduction, safe disposal of high-level radioactive waste, and use of computed tomography as a diagnostic screening tool. Dr. Locke directs the School's Doctor of Public Health program in Environmental Health Sciences. He was a member of the National Research Council Nuclear and Radiation Studies Board from 2003 to 2009, and has served on five National Research Council committees. He is also a member of the editorial boards of *Risk Analysis: An International Journal* and the *International Journal of Low Radiation* and is on the Board of Directors of the National Council on Radiation Protection and Measurements. He is admitted to practice law in the states of New York and New Jersey, the District of Columbia, the Southern District Court of New York and the U.S. Supreme Court.

Corby Anderson is the Harrison Western Professor of Metallurgical and Materials Engineering at the Colorado School of Mines. Dr. Anderson is an expert in the fields of mineral processing, chemical metallurgy, and waste minimiza-

tion and recycling, has an extensive background in industrial-oriented research, and has more than 30 years of academic and applied experience in mining, chemical, and materials engineering. In 2008, he received the Milton Wadsworth Award from the Society for Mining, Metallurgy, and Exploration for his contributions to advance the field of chemical metallurgy. Dr. Anderson holds a Ph.D. in mining engineering–metallurgy from the University of Idaho, as well as a Bachelor's degree in chemical engineering and a Master's degree in metallurgical engineering.

Lawrence W. Barnthouse is the president and principal scientist of LWB Environmental Services, Inc. His consulting activities include 316(b) demonstrations for nuclear and nonnuclear power plants, Superfund ecological risk assessments, natural resource damage assessments, risk-based environmental restoration planning, and a variety of other projects involving close interactions with regulatory and resource management agencies. Dr. Barnthouse has authored or coauthored more than 90 publications relating to ecological risk assessment. He is a fellow of the American Association for the Advancement of Science, Hazard/Risk Assessment Editor of the journal *Environmental Toxicology and Chemistry*, and founding editorial board member of the new journal *Integrated Environmental Assessment and Management.* He has served on the National Research Council Board on Environmental Studies and Toxicology and on several National Research Council committees, and was a member of the peer review panel for the U.S. Environmental Protection Agency's Guidelines for Ecological Risk Assessment. Dr. Barnthouse holds a Ph.D. in biology from the University of Chicago.

Paul D. Blanc is Professor in Residence and Endowed Chair of the Division of Occupational and Environmental Medicine in the Department of Medicine at the University of California, San Francisco (UCSF). Dr. Blanc also has secondary appointments to the Department of Medical Anthropology, Social Medicine, and History of Medicine and the Department of Clinical Pharmacy at UCSF. His current research interests include the epidemiology of occupational lung disease, asthma and chronic obstructive pulmonary disease outcomes, and occupational toxicology. Dr. Blanc previously served on the Institute of Medicine Committee to Review the NIOSH Respiratory Disease Research Programand the Committee on Poison Prevention and Control. He has an M.S.P.H. from the Harvard School of Public Health and his M.D. from the Albert Einstein College of Medicine. Dr. Blanc serves as the University of California designee and California State Senate appointee to the Scientific Review Panel on Toxic Air Contaminants for the Air Resources Board of the State of California. He is the author of *How Everyday Products Make People Sick* (University of California Press).

Scott C. Brooks is senior scientist in the Environmental Sciences Division of Oak Ridge National Laboratory. Dr. Brooks' research focuses on the biogeochemistry

of advecting fluids in the subsurface and the geochemical factors influencing the fate and transport of solutes. He has conducted numerous experiments at the laboratory and field scales, studying the fate and transformation of radionuclides in the environment. He has Ph.D. and M.S. degrees in environmental sciences from the University of Virginia.

Patricia Buffler (IOM) is professor of epidemiology and holds the Kenneth and Marjorie Kaiser Chair in Cancer Epidemiology in the School of Public Health at the University of California, Berkeley. Dr. Buffler's research interests include the environmental causes of cancer, especially gene–environment interaction and childhood cancer, lung cancer, leukemia, brain cancer, and breast cancer; epidemiological research methods; and the uses of epidemiological data in health policy. She has served on numerous committees of the National Research Council, including the Committee on Health Risks from Exposure to Low Levels of Ionizing Radiation, and Committee on Emerging Issues and Data on Environmental Contaminants. Dr. Buffler was elected to the Institute of Medicine in 1994. She received a Ph.D. in epidemiology from the University of California, Berkeley.

Michel Cuney is director of the research team, Genesis and Management of Mineral Resources for the National Center for Scientific Research (CNRS) at the Henri Poincaré University in Nancy, France. He has worked mainly on the geochemistry of uranium in various geological environments since 1972. He has visited and/or worked on most major uranium deposits of the world, and has published about 180 scientific papers in this disciplinary area. Dr. Cuney is one of the world's experts on the genesis of uranium deposits and uranium geology, and he will provide invaluable insights concerning mining techniques that would be used to extract uranium from deposits in Virginia as well as the possible effects on the local environment. Dr. Cuney received his Docteur es Sciences (Ph.D.) degree from Henri Poincaré University.

Peter L. DeFur is president of Environmental Stewardship Concepts, LLC (ESC), an independent private consulting firm in Richmond, Virginia. He is also an affiliate associate professor at the Center for Environmental Studies, Virginia Commonwealth University, where he conducts research on environmental health and ecological risk assessment. Dr. DeFur has over 30 years' experience providing technical services regarding the cleanup of contaminated sites to community organizations across the country. Dr. DeFur received B.S. and M.S. degrees from the College of William and Mary, and a Ph.D. in biology from the University of Calgary.

Mary English is a senior fellow at the Institute for a Secure and Sustainable Environment, the University of Tennessee in Knoxville. She is a social scientist who is familiar with the environmental effects of mining and related regulatory issues.

Her work has focused on energy and environmental policy and has included research on mechanisms for involving stakeholders in public policy decisions, how "the community" should be defined within the context of community-based environmental efforts, information gathering and analytical tools to improve environmental decision making, and guidance on conducting socioeconomic impact assessments. She previously served on the National Research Council Board on Radioactive Waste Management as well as the National Research Council Board on Environmental Studies and Toxicology. Dr. English has an M.S. from the University of Massachusetts and a Ph.D. in sociology from the University of Tennessee, Knoxville.

Keith N. Eshleman is a professor at the University of Maryland Center for Environmental Science based at the Appalachian Laboratory in Frostburg, Maryland. Dr. Eshleman's professional expertise is in the field of watershed hydrology, having completed his Ph.D. in water resources at Massachusetts Institute of Technology (MIT) in 1985. Dr. Eshleman also holds a B.A. in environmental sciences from the University of Virginia (1978) and an S.M. in Civil Engineering from MIT (1982). Dr. Eshleman has published more than 50 peer-reviewed papers and dozens of technical reports in his career and is coauthor of an undergraduate textbook entitled *Elements of Physical Hydrology* (with former colleagues from the University of Virginia, where Dr. Eshleman served on the faculty from 1988 through 1995). Dr. Eshleman's research interests are in the areas of watershed and wetlands hydrology, groundwater–surface water interactions, biogeochemical processes in upland and wetland ecosystems, hydrochemical modeling, and ecosystem responses to disturbance and land-use change. Recent research projects have focused on the hydrological impacts of acid deposition, forest disturbances, and surface mining activities in the Appalachian Mountain region.

R. William Field is a professor in the Department of Occupational and Environmental Health and in the Department of Epidemiology at the University of Iowa's College of Public Health. He is also a professor of toxicology and health informatics within the Graduate College at the University of Iowa. In addition, he serves as the director of the Occupational Epidemiology Training Program at the National Institute for Occupational Safety an Health Heartland Center for Occupational Health and Safety, and director of the Pulmonary Outcomes Cluster, National Institute for Environmental Health Sciences, Environmental Health Sciences Research Center. Dr. Field has been active in numerous national and international collaborative radiation-related epidemiolgical projects and has served on the editorial boards of several national and international scientific journals. He is a member of the U.S. Environmental Protection Agency's Science Advisory Board, Radiation Advisory Committee, and was appointed by President Obama in 2009 to the Advisory Board on Radiation and Worker Health. Dr. Field

received his Ph.D. in preventive medicine from the College of Medicine at the University of Iowa.

Jill Lipoti is director of the Division of Water Monitoring and Standards at the New Jersey Department of Environmental Protection. Prior to assuming this position, she was director of the Division of Environmental Safety and Health with responsibility for directing the state's radiation protection programs. Dr. Lipoti also serves as adjunct assistant professor, University of Medicine and Dentistry of New Jersey, School of Public Health, Department of Environmental and Occupational Health, specializing in radiation exposure and preparedness for chemical and radiological emergencies. She has provided advice to the International Atomic Energy Agency regarding radiation safety and security, and has chaired the Radiation Advisory Committee of the U.S. Environmental Protection Agency's Science Advisory Board. She has M.S. and Ph.D. degrees in environmental science from Rutgers University.

Henry A. Schnell holds the position of technical authority (senior expert) in the Expertise & Technical Department, Mining Business Unit, with AREVA NC Inc. In his role as technical authority for uranium, he is responsible for review and support of existing operations and new projects worldwide, and for final technical authorization of plant design and modifications. Mr. Schnell has 41 years of experience in management, plant operations, plant design, engineering, and research and development in mining and ore treatment, and 21 years of this has been specializing in uranium metallurgy, operations, and mining projects. He has a B.S. (Honours) from the University of Alberta, Edmonton, and other extensive training in metallurgy and project management.

Jeffrey J. Wong is deputy director of the science, Pollution Prevention and Technology Program for the California Department of Toxic Substances Control (DTSC) at the California Environmental Protection Agency and serves as DTSC's chief scientist. This program's activities include environmental measurements, biological and exposure monitoring, toxicology and risk assessment, and green chemistry and pollution prevention. Before his current appointment, Dr. Wong served as chief of DTSC's Human and Ecological Risk Division. He served by presidential appointment on the U.S. Nuclear Waste Technical Review Board from 1996 until 2002. Dr. Wong has served on several National Academies committees, including the Committee on Risk-Based Approaches for Disposition of Transuranic and High-Level Radioactive Waste, the Committee on Environmental Remediation at Naval Facilities, the Committee on Remedial Action Priorities for Hazardous Waste Sites, and the Panel for Review of the DOE Environmental Restoration Priority System. Dr. Wong received his Ph.D. in pharmacology and toxicology from the University of California, Davis.

NATIONAL RESEARCH COUNCIL STAFF

David A. Feary is a senior program officer with the National Research Council's Board on Earth Sciences and Resources. He earned his Ph.D. at the Australian National University, before spending 15 years as a research scientist with the marine program at Geoscience Australia. During that time, he participated in numerous research cruises—many as chief or co-chief scientist—and was co-chief scientist for Ocean Drilling Program Leg 182. His research activities have focused on the role of climate as a primary control on carbonate reef formation, and improved understanding of cool-water carbonate depositional processes. He also holds a joint appointment as research professor in the School of Earth and Space Exploration and the School of Sustainability at Arizona State University.

Stephanie Johnson is a senior program officer with the Water Science and Technology Board. Since joining the National Research Council in 2002, she has served as study director for 12 studies, including congressionally mandated reviews of Everglades restoration progress. She has also worked on National Research Council studies on desalination, water reuse, contaminant source remediation, the disposal of coal combustion wastes, and water security. Dr. Johnson received a B.A. from Vanderbilt University in chemistry and geology and an M.S. and a Ph.D. in environmental sciences from the University of Virginia.

Courtney R. Gibbs is a program associate with the National Research Council Board on Earth Sciences and Resources. She received her degree in graphic design from the Pittsburgh Technical Institute in 2000 and began working for the National Academies in 2004. Prior to her work with the board, Ms. Gibbs supported the Nuclear and Radiation Studies Board and the former Board on Radiation Effects Research.

Nicholas D. Rogers is a financial and research associate with the National Research Council Board on Earth Sciences and Resources. He received a B.A. in history, with a focus on the history of science and early American history, from Western Connecticut State University in 2004. He began working for the National Academies in 2006 and has primarily supported the board on a broad array of Earth resources, mapping, and geographical sciences issues.

Appendix C

World Nuclear Association Basic Principles

The following material is taken verbatim from a World Nuclear Association (WNA) policy document "Sustaining Global Best Practices in Uranium Mining and Processing—Principles for Managing Radiation, Health and Safety, Waste and the Environment."[1] The WNA is an international organization with the goal of promoting nuclear energy and a mission to seek to foster interaction among top industry leaders to help shape the future of nuclear power.

PRINCIPLE 1: ADHERENCE TO SUSTAINABLE DEVELOPMENT

Conduct all aspects of uranium mining and processing with full adherence to the principles of sustainable development as set forth by the International Council on Mining and Metals. Apply these principles with emphasis on excellence in professional skills, transparency in operations, accountability of management, and an overarching recognition of the congruency of good business and sound environmental practices.

Discussion: *In establishing its sustainable development principles, the ICMM adopted the landmark definition of that term advanced by the Brundtland Commission: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." To this the ICMM added: "In the mining and metals sector . . . investments should be financially profitable, technically appropriate, environmentally sound and socially responsible."*

In emphasizing the practical necessity of financial profitability, the ICMM underscored that economic profitability and sustainable development, far from

[1]See http://www.world-nuclear.org; accessed October 2011.

being at odds, must be consistent and reinforcing goals. This congruency of purpose is reflected in the ICMM commitment to "seek continual improvement in performance and contribution to sustainable development so as to enhance shareholder values."

PRINCIPLE 2: HEALTH, SAFETY AND ENVIRONMENTAL PROTECTION

In all management practices, ensure adequate protection of employees, contractors, communities, the general public, and the environment, as follows:

***Mining Safety*—**Ensure safe, well maintained site conditions for the protection of employees and the public from all conventional mining hazards, including those related to airborne contaminants, ground stability and structure, geological and hydro-geological conditions, storage and handling of explosives, mine flooding, mobile and stationary equipment, ingress and egress, and fire.

***Radiation Safety*—**Comply with the principles of Justification, Optimization and Limitation, as follows:

Justification: Authorize the introduction of any new practice involving radiation exposure, or the introduction of a new source of radiation exposure within a practice, only if the practice can be justified as producing sufficient benefit to the exposed individuals or to society to offset any potential radiation harm.

Optimization and Limitation: Optimize radiation exposure to as low as reasonably achievable, taking into account all socio-economic factors. Ensure compliance with the occupational and public dose limits laid down by the appropriate national and international regulatory and advisory bodies. In so doing, classify, according to risk, site personnel and work areas that are subject to radiation exposure. Plan and carefully monitor employee and contractor doses, radioactive discharges and emissions as well as resulting environmental concentrations and exposure rates. Estimate potential radiological impacts on the public and the environment.

***Personal Protective Equipment*—**Ensure that employees and visitors are provided personal protective equipment (PPE) appropriate for the hazard being controlled and compliant with relevant standards or specifications to control exposure to safe levels. Ensure that relevant personnel remain properly trained on the use and maintenance of this equipment.

***Ventilation*—**Ensure that workplaces are adequately ventilated and that airborne contaminants are minimized in workplaces. Pay particular attention to controlling radon and related radiation exposures in uranium mines and processing facilities.

***Water Quality*—**Develop and implement site-specific water management practices that meet defined water-quality objectives for surface and ground waters (focusing particular attention on potable water supplies). Subject water-quality objectives to periodic review to ensure that people and the environment remain protected.

Environmental Protection—Overall, avoid the pollution of water, soil and air; optimize the use of natural resources and energy; and minimize any impact from the site and its activities on people and the environment. In so doing, include considerations of sustainability, bio-diversity and ecology in guarding against environmental impact.

PRINCIPLE 3: COMPLIANCE

Support the establishment of a suitable legal framework and relevant infrastructure for the management and control of radiation, occupational and public health and safety, waste and the environment. Ensure that all activities are authorized by relevant authorities and conducted in full compliance with applicable conventions, laws, regulations and requirements, including in particular the Safety Standard Principles of the International Atomic Energy Agency (IAEA). Do so with careful consideration to the applicable IAEA Safety Standards. In recognition that effective interaction of operators (including contractors) and the appropriate regulatory authorities is essential to safety, ensure that operators and contractors are licensed, having met the requirement of relevant authorities.

PRINCIPLE 4: SOCIAL RESPONSIBILITY

At all stages of uranium mining and processing, properly inform—and seek, gain, and maintain support from—all potentially affected stakeholders, including employees, contractors, host communities, and the general public. Establish an open dialogue with affected stakeholders, carefully consider their views, and provide feedback as to how their concerns are addressed. (See the WNA Charter of Ethics in Annex 1 and, in Principle 6 herein, the text on Environmental Impact Assessment.)

PRINCIPLE 5: MANAGEMENT OF HAZARDOUS MATERIALS

Manage and dispose of all hazardous materials (radioactive or non-radioactive)—including products, residues, wastes and contaminated materials—in a manner that is safe, secure and compliant with laws and regulations.

Management of Hazardous Wastes and Contaminated Materials Act systematically to establish and implement controls to minimize risks from such wastes and contaminated materials. Take actions to maintain and treat sources of hazardous materials on-site wherever it is practicable to do so. Control and minimize any releases into the environment, using carefully planned strategies that involve pollution control technologies, robust environmental monitoring, and predictive modelling to ensure that people and the environment remain well protected. Rely where possible on proven, best available, industry-scale technologies. Focus particular attention on managing ore stockpiles and such potentially

significant sources of contamination as waste rock, tailings, and contaminated water or soils. With tailings, concentrate special effort on the design and construction of impoundments and dams and on the application of a recognized tailings management system for operations, monitoring, maintenance, and closure planning. Use risk analysis and controls to account for current and long-term stability of waste repositories and containment. As an integral aspect of mining and processing, characterize ore and waste rock. Consider the geochemistry and assess the risk of acid rock drainage (ARD); where ARD could occur, develop an ARD management plan which accounts for ARD-producing ore, reject materials and gangue, and which provides for appropriate scheduling of mining, stockpile segregation, processing and contaminant containment. Use effective containment designs to ensure against long-term liability from ARD-producing rock. Use all opportunities to reduce the creation of hazardous wastes and contaminated materials. To the extent practicable, recover, recycle and re-use such wastes and materials, regarding waste disposal as a last-resort option. From each site, control the release or removal of wastes and contaminated materials, using a chain-of-custody approach where needed. Safely manage all off-site streams for hazardous materials and contaminated wastes.

PRINCIPLE 6: QUALITY MANAGEMENT SYSTEM

Employ a recognized quality management system—including the quality-assurance steps of Plan, Do, Check and Act (PDCA)—in administering the management of all activities pertinent to radiation, health and safety, waste and the environment.

***Planning*—**At all development and operational stages, plan for the management of radiation, health and safety, waste and the environment. With the constant goal of avoiding risk and optimizing the use of natural resources and energy, update such plans regularly, and particularly in response to any significant change in activities or site conditions. Include, as a central element in such plans, steps for the control of emergencies and unplanned events. Ensure that plans are well documented and communicated. In developing a uranium mining or processing project, prepare a formal Environmental Impact Assessment (EIA) that deals with all questions and concerns related to radiation, occupational and public health and safety, waste and the environment, as well as socio-economic impact. Submit the EIA as part of the public review process so as to provide response opportunities for stakeholders, especially the workforce and host communities. During the life of a project, prepare further EIAs if and as warranted by new circumstances.

***Risk Management*—**Apply risk assessment and management procedures to radiation, occupational and public health and safety, waste and the environment. Identify, characterize and assess all risks that can impact on health, safety and environmental protection. Mitigate risks with controls in engineering, administration and other protective measures. Apply a hierarchy of risks and con-

trols. Monitor risks and take timely action to offset the emergence of new risks. Regularly review performance to improve procedures, further reduce risk, detect weaknesses and trigger corrective measures. Document and report relevant data, and maintain records in compliance with regulatory requirements. Place special emphasis on data required and acquired by the quality assurance management system.

PRINCIPLE 7: ACCIDENTS AND EMERGENCIES

Identify, characterize and assess the potential for incidents and accidents, and apply controls to minimize the likelihood of occurrence. Develop, implement and periodically test emergency preparedness and response plans. Ensure the availability of mechanisms for reporting and investigating all incidents and accidents so as to identify "root cause" and facilitate corrective actions.

PRINCIPLE 8: TRANSPORT OF HAZARDOUS MATERIALS

Package and transport all hazardous materials (radioactive and non-radioactive)—including products, residues, wastes, and contaminated materials—safely, securely, and in compliance with laws and regulations. With radioactive materials, adhere to IAEA Regulations for the Safe Transport of Radioactive Material, relevant IAEA Safety Guides, applicable international conventions, and local legislation.

PRINCIPLE 9: SYSTEMATIC APPROACH TO TRAINING

In each area of risk, provide systematic training to all site personnel (employees and contractors) to ensure competence and qualification; include in such training the handling of non-routine responsibilities. Extend such training, where appropriate, to visitors and relevant persons in communities potentially affected by these risks. Regularly review and update this training.

PRINCIPLE 10: SECURITY OF SEALED RADIOACTIVE SOURCES AND NUCLEAR SUBSTANCES

Ensure the security of sealed radioactive sources and nuclear substances, using the chain-of-custody approach where practicable and effective. Comply with applicable laws, international conventions and treaties, and agreements entered into with stakeholders on the safety and security of such sources and substances.

PRINCIPLE 11: DECOMMISSIONING AND SITE CLOSURE

In designing any installation, plan for future site decommissioning, remediation, closure and land re-use as an integral and necessary part of original project development. In such design and in facility operations, seek to maximize the use of remedial actions concurrent with production. Ensure that the long-term plan includes socio-economic considerations, including the welfare of workers and host communities, and clear provisions for the accumulation of resources adequate to implement the plan. Periodically review and update the plan in light of new circumstances and in consultation with affected stakeholders. In connection with the cessation of operations, establish a decommissioning organization to implement the plan and safely restore the site for re-use to the fullest extent practicable. Engage in no activities—or acts of omission—that could result in the abandonment of a site without plans and resources for full and effective decommissioning or that would pose a burden or threat to future generations.

Appendix D

IRPA Guiding Principles for Stakeholder Engagement

The following material is taken verbatim from an International Radiation Protection Association (IRPA) document *"IRPA Guiding Principles for Radiation Protection Professionals on Stakeholder Engagement."*[1] The IRPA is an international professional association focused on radiation protection, that seeks to enable improved communication among those engaged in radiation protection activities in all countries so that radiation protection can be improved worldwide.

[1] See http://www.irpa.net/; accessed October, 2011.

IRPA Guiding Principles for Radiation Protection Professionals on Stakeholder Engagement

INTRODUCTION

During the 11th Congress of the International Radiation Protection Association (IRPA) held in Madrid in May 2004 there were considerable discussions on the benefits of involving all relevant parties in the decision-making processes related to radiological protection. It was agreed that this involvement, briefly described as "Stakeholder Engagement", should play an important and integral part in these processes. A need was identified for guidance to be produced to help radiation protection professionals to understand the objectives, requirements and demands of stakeholder engagement, encourage participation and provide a framework for establishing a constructive dialogue with other stakeholders.

As a result of these discussions a group of professionals from the French, Spanish and UK IRPA Associate Societies decided to collaborate in organising a series of workshops to exchange information especially on case studies of how stakeholder involvement had been carried out in different fields of radiation protection. The workshops were held in Salamanca, Spain, November 2005, Montbéliard, France, December 2006 and Oxford, UK, December 2007 and resulted in a draft version of the Guiding Principles. During the course of this development the progress was systematically reported to meetings of the IRPA Executive Council and at IRPA Regional Congresses (Paris, France in May 2006, Acapulco, Mexico in September 2006, Beijing, China in October 2006, Cairo, Egypt in April 2007 and Brasov, Romania in September 2007).

The draft version of the Guiding Principles was sent to all Associate Societies for comments in Spring 2008. After revision by the Executive Council the Guiding Principles were presented at the IRPA 12 Associate Societies Forum and, after discussion and with some amendments, endorsed by the Forum. The Guiding Principles were finally adopted formally on 18 October 2008 in Buenos Aires by the IRPA Executive Council.

These Guiding Principles are intended to aid members of IRPA Associate Societies in promoting the participation of all relevant parties in the process of reaching decisions involving radiological protection which may impact on the well being and quality of life of workers and members of the public, and on the environment. In promoting this approach, radiological protection professionals will aim to develop trust and credibility throughout the decision making process in order to improve the sustainability of any final decisions.

PRINCIPLES

Radiological protection professionals should endeavour to:

1. Identify opportunities for engagement and ensure the level of engagement is proportionate to the nature of the radiation protection issues and their context.
2. Initiate the process as early as possible, and develop a sustainable implementation plan.
3. Enable an open, inclusive and transparent stakeholder engagement process.
4. Seek out and involve relevant stakeholders and experts.
5. Ensure that the roles and responsibilities of all participants, and the rules for cooperation are clearly defined
6. Collectively develop objectives for the stakeholder engagement process, based on a shared understanding of issues and boundaries.
7. Develop a culture which values a shared language and understanding, and favours collective learning.
8. Respect and value the expression of different perspectives.
9. Ensure a regular feedback mechanism is in place to inform and improve current and future stakeholder engagement processes.
10. Apply the IRPA Code of Ethics in their actions within these processes to the best of their knowledge.

GUIDANCE

Principle 1

Identify opportunities for engagement and ensure the level of engagement is proportionate to the nature of the radiation protection issues at stake and their context.

The primary purpose of engagement is to contribute to decision making on radiological protection measures so that;

- the measures are more widely understood and respected;
- the measures are optimal and work in practice across a broad range of foreseeable situations;
- the measures are tailored to the local context (social, economic, environmental etc);
- the measures will continue to be effective and have credibility for some reasonable period of time.

Engagement will add real value to the decision-aiding process and its outcome but its extent and nature need to be proportionate to the radiation protection

issues and concerns at stake. This includes being realistic about the co-operation that can be achieved and about the resources and time that might need to be expended on interacting with the more challenging stakeholders. The more complex the radiological protection problem and the more serious the risk, or even the perception of the risk, the greater is the justifiable investment in engagement.

In identifying opportunities for engagement it is important to be aware of changing societal expectations. Changes such as increasing awareness about the risks associated with some activities, concerns over environmental deterioration or loss of public confidence in some organisations are all likely to broaden or shift the range of stakeholders that need to be engaged.

Principle 2

Initiate the process as early as possible and develop a sustainable implementation plan

Feed-back experience has shown that involving stakeholders, as early as possible, in decision-aiding processes will generally improve the mutual understanding of the situation, and therefore may avoid reaching a deadlock at a later stage. Although it may increase the duration of the process, involving stakeholders will generally facilitate better cooperation between all participants and lead to more acceptable and robust decisions.

At the early stage of the decision-aiding process, involving stakeholders will give the opportunity to develop together a sustainable plan in terms of scope, objectives, timetable and milestones, deliverables, knowledge production, financial support etc. In order to improve the sustainability of the process, a reasonable approach, shared by all participants, should be adopted when defining this plan. The process has to be proportionate to the realities of the situation, and take into account the stakeholders' time and opportunity to participate according to their particular circumstances. Finally, it has to be kept in mind that it will be necessary to revise and adapt the plan as the situation evolves.

Principle 3

Enable an open, inclusive and transparent stakeholder engagement process

Openness, inclusiveness and transparency, which are interrelated, should constitute the essence of a successful stakeholder engagement process and should always be present. They are the basis for understanding, creating confidence in the process and promoting it. They may be supported by collectively agreed rules and mechanisms for their assessment.

The process should include all the relevant stakeholders, extending representation beyond the obvious candidates to all those perceived to have a share

in or an impact associated with the risks of the endeavour under consideration. Different expertise and sensibilities will generally enrich the process and give more validity to the results.

All the issues entering into the decision should be considered, with openness, to identify, select and discuss any associated uncertainties.

During the process, it is important to share the information needed to build a collective understanding of the problem, starting in particular with risk communication. The flow of information should be quick, concise, clear to all and honest (in terms of accuracy, uncertainty etc.). By default, information should be accessible to all, but recognising that some information truly requires protection. Rather than withholding information on grounds of personal or national security or confidentiality, it is preferable to have it presented in a different way, rather than agree its omission.

It would be helpful to build, grow, review and maintain a common knowledge pool, identifying a responsible 'gatekeeper' or 'custodian' for the knowledge pool who is trusted and respected by all parties.

Principle 4

Seek out and involve relevant stakeholders and experts.

A key part of decision-aiding is to be very clear over what is the issue in question, the scope of the problem and the factors that may be relevant. Inherent to this process is the need to identify those who can and should contribute; in short, ensuring that an appropriate diverse range of views are included. The radiological protection professional can help to promote this approach, as radiological protection is, by its nature, an interdisciplinary science.

There is a need to reach out to other disciplines and stakeholders, making them aware of the issues under consideration. Without this first step relevant factors may not come to light, undermining the validity and sustainability of any decisions. For example experts in one discipline may not be aware of knock on effects in other areas. Similarly if the net of consultation has been set wide enough to elicit "no comment" replies, this is useful information to support the bounding of the issue. Bringing together all the diverse views may be an iterative process, particularly for large scale decision making that may involve socio-economic factors. Thus it should be accepted that the initial set of stakeholders may not be the final set. The process can be a dynamic one with stakeholders joining, but also leaving, throughout.

There is a need to have respect for information and knowledge gained through individuals' experience as well as that from scientific and technical experts. Some issues, particularly high profile ones, bring with them stakeholders with significantly different points of views. It is important that there is engagement with, rather than avoidance of, these different groups. Inevitably there

will be conflicting views and information. How these are evaluated within the decision-aiding process is a separate but important element (see principles 3 and 5), however it is clear that obtaining a full spectrum of views is important.

Principle 5

Ensure that the roles and responsibilities of all participants, and the rules for cooperation are clearly defined

A clear definition, at the beginning of the process, of the roles and responsibilities of the different categories of participants (for example, experts, authorities, sponsors, lay persons, decision maker versus decision taker, . . .), is important to obtain a shared understanding of what is expected from each and the extent of the influence they may have. In addition it will be helpful to set out clearly the rules under which cooperation can be achieved. A clear delineation of the consultation phase and the decision phase, as well as a clear understanding of where individuals' responsibilities and accountabilities begin and end is essential to clarify the conditions of the engagement. Potential conflicts of interest should be declared by all parties. It may be helpful for radiological protection professionals to make reference to their own Code of Ethics.

One of the objectives of stakeholder engagement in a decision-aiding process is to promote dialogue and mutual understanding, but not necessarily to reach a consensus on all aspects of the situation. It is thus important to preserve the autonomy of the different categories of participants concerning their points of view or their evaluation of the situation. This delineation of roles is a key element to create the conditions for the participants to contribute to the improvement of the evaluation of the situation and the radiation protection options.

Beyond clarifying the roles and responsibilities, sharing the rules of cooperation between the participants will also favour the success of the process.

Principle 6

Collectively develop objectives for the stakeholder engagement process, based on a shared understanding of issues and boundaries.

The need for a collective approach to developing process objectives is implied by application of the other principles. Principle 2 talks of the development of a sustainable plan, Principle 4 of identifying the responsibility of contributors and of scoping problems and factors, and Principle 5 of the need to co-operate.

Lack of collectivism disenfranchises stakeholders, whereas working alongside each other allows a tight group to emerge which is then capable of explicitly defining the process objectives. The group is then in a position to validate these

against its shared understanding of issues and boundaries, as well as to collectively agree the scope or remit for the work.

Once the objectives are identified in principle then the discussions can extend to ensuring that they are refined in the light of the resources available. The realism brought about by this dialogue invariably leads to more harmonious working by avoiding feelings of frustration with the process that might be perceived as more imposed than negotiated.

Principle 7

Develop a culture which values a shared language and understanding, and favours collective learning.

In order for all stakeholders to fully appreciate the factors entering into the decision they must be able to understand what is being said. This understanding can be seriously compromised by the use of jargon and technical language as well as acronyms and abbreviations. The radiological protection professional should be motivated to develop a "common language" sufficiently precise scientifically not to offend the various experts but also sufficiently rooted in common, everyday experience to be meaningful to all those involved. Part of this approach is likely to involve formal and informal training of stakeholders leading to the creation of a shared knowledge base incorporating those technical concepts essential to a full understanding of the issues.

Principle 8

Respect and value the expression of different perspectives.

It is important that each participant in the process recognises their own and each others' uniqueness, and, because of this, is aware that other participants have different backgrounds and sensibilities and, therefore, may view issues from different perspectives.

Participants should be aware that some may be experts in their own field, and the integration of their views is an important step in the process, whilst accepting challenges to expert opinion. Evaluation of uncertainties in the assessments where expert opinion is divided should be undertaken in an open, accessible and clear manner. Experts should recognise the limits of their mandate.

Respect for one another's view encourages a wide range of thoughts and ideas which can be evaluated as a whole during the engagement process. This acceptance of diverse perspectives, thinking and values has the potential to enrich the process, providing that the process is controlled such that any entrenched views and ideologies, if present, are managed by agreed mechanisms. In a similar way, seemingly radical or novel opinions should not be dismissed out of hand, but

evaluated with respect in the same way as other ideas. It is important that each individual can see their own contribution in the record of the meetings.

Participants should be aware that rational thought, respect and acceptance of opinions will tend to be challenged or obscured when discussing issues which are emotive, or issues which have attracted significant media or political interest. Efforts should be made if this happens to restore the desirable climate of mutual respect and cooperation.

Principle 9

Ensure a regular feedback mechanism is in place to inform and improve current and future stakeholder engagement processes

When engaging with stakeholders an opportunity should be provided for both the stakeholders and those responsible for the process to give feedback on the approaches and tools used and on the outcomes. This serves to inform and improve ongoing processes as well as influencing how future processes should be conducted. The following types of criteria might be included in the evaluation: appropriateness of the terms and timing of engagement, the quality and appropriateness of the information provided; comprehensiveness of the issues that were addressed; inclusivity in terms of the number and diversity of stakeholders involved and the nature of that engagement; practicability and feasibility of the eventual outcomes.

Stakeholder engagement commonly involves a series of meetings, discussions and other types of face-to-face encounters. These provide continuous learning opportunities to be discussed by the group at the end of each meeting, whereby agreements on improvements in the management of subsequent meetings are agreed. It should be recognised that implementation of changes may require additional resources and so any improvements agreed upon must be realistic and achievable.

When a stakeholder engagement process comes to an end, it is important that those responsible for the process make the results known to all those who participated. If these results do not reflect the recommendations or findings from the stakeholders, those responsible must offer an explanation to the stakeholders for any deviation from what was agreed. In this way, the feedback of results and decisions will help to maintain confidence in the process.

Tangible improvements in stakeholder engagement resulting from the establishment of a constructive feedback mechanism will contribute to a more sustainable process, which could serve as a role model for future engagement. Dissemination of the lessons learned, achievements and how challenges can be met should be carried out as widely as possible among the radiological protection community.

Principle 10

Apply the IRPA Code of Ethics in their actions within these processes to the best of their knowledge.

Throughout the stakeholder engagement process, the radiological protection professional should be bound by the IRPA Code of Ethics or an equivalent National Code.

Appendix E

Presentations to Committee

MEETING 1—OCTOBER 26-28, 2010
Washington, D.C.

R. Lee Ware, Virginia House of Delegates
Michael Karmis, Virginia Polytechnic Institute and State University
Loren Setlow, U.S. Environmental Protection Agency
David Geiser, U.S. Department of Energy
Scott Sitzer, DOE Energy Information Administration
Jim Otton, U.S. Geological Survey
Bob Seal, U.S. Geological Survey
Ed Landa, U.S. Geological Survey
Dave Nelms, U.S. Geological Survey

MEETING 2—NOVEMBER 15-16, 2010
Washington, D.C.

William von Till, U.S. Nuclear Regulatory Commission
Jim Weeks, Mine Safety and Health Administration
Larry J. Elliot, National Institute for Occupational Safety and Health
Charles W. Miller, Centers for Disease Control and Prevention
Katie Sweeney, National Mining Association
Geoffrey Fettus, Natural Resources Defense Council

MEETING 3—DECEMBER 13-15, 2010
Danville, Virginia

Cale Jaffe and Robert G. Burnley, Southern Environmental Law Center
Todd Benson, Piedmont Environmental Council
Katherine Mull, Dan River Basin Association
Andrew Lester, Roanoke River Basin Association
Ray Ganthner, Virginia Energy Independence Alliance
Patrick Wales, Virginia Uranium Inc.
Norm Reynolds, Virginia Energy Resources
William Lassetter, Virginia Department of Mines, Minerals and Energy
Robert Bodnar, Virginia Polytechnic Institute and State University

MEETING 4—FEBRUARY 6-8, 2011
Richmond, Virginia

Tom Leahy, City of Virginia Beach
James S. Beard, Virginia Museum of Natural History
Conrad Spangler, Virginia Department of Mines, Minerals and Energy
David A. Johnson, Virginia Department of Conservation and Recreation
David K. Paylor, Virginia Department of Environmental Quality

MEETING 5—MARCH 23-25, 2011
Boulder, Colorado

Thomas Johnson, Colorado State University
Jonathan Samet, University of Southern California
Phillip Egidi, Colorado Department of Public Health and the Environment
Paul Robinson, Southwest Research and Information Center

MEETING 6—JUNE 6-10, 2011
Saskatoon, Canada

Hugh B. Miller, Colorado School of Mines
Dirk van Zyl, University of British Columbia
Kevin Scissons, Canadian Nuclear Safety Commission
Gary Delaney, Saskatchewan Geological Survey
Cory Hughes, Saskatchewan Geological Survey
Tim Moulding, Saskatchewan Ministry of Environment
James Keil, Saskatchewan Ministry of Labour Relations and Workplace Safety Radiation
Theresa McClenaghan, Canadian Environmental Law Association
Richard Gladue, AREVA Resources Canada, Inc.

Dale Huffman, AREVA Resources Canada, Inc.
Wayne Summach, Cameco Corporation

MEETING 7—SEPTEMBER 6-8, 2011
Irvine, California

The committee's final meeting was entirely in closed session, with no external presentations.

Appendix F

Acronyms and Abbreviations

AEA	Atomic Energy Act
ALARA	as low as reasonably achievable
ALI	annual limit on intake
AMD	acid mine drainage
ANFO	ammonium nitrate fertilizer and fuel oil
ATSDR	Agency for Toxic Substances and Disease Registry
BEIR	National Research Council Committee on the Biological Effects of Ionizing Radiation
Bq	Becquerel
CAA	Clean Air Act
California EPA	California Environmental Protection Agency
CDC	Centers for Disease Control and Prevention
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CI	confidence interval
Ci	Curie
cm/s	cubic meters per second
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CT	computerized tomography
CWA	Clean Water Act

DAC	derived air concentration
EAR	estimated additional resources
EIA	environmental impact assessment
EIS	environmental impact statement
ESRD	end-stage renal disease
Ga	billion years ago
GWe	Gigawatt equivalent
Gy	Gray (unit)
HKCa	highly potassic calc-alkaline magmas
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
IR	Inferred Resources
ISL	in situ leaching
ISR	in situ recovery (term used primarily in North America)
K	potassium
km	kilometers
m	meters
MCL	maximum contaminant level
µg/L	micrograms per liter
µGy/h	microGrays/hour
MOU	Memorandum of Understanding
MOX	mixed oxide
MSHA	Mine Safety and Health Administration
MVOCs	microbial volatile organic compounds
My	million years old
Nb	niobium
NCI	National Cancer Institute
NCRP	National Council on Radiation Protection and Measurements
NEA	Nuclear Energy Agency of the Organisation for Economic Co-Operation and Development
NIOSH	National Institute for Occupational Safety and Health
NLM	National Library of Medicine
NORM	naturally occurring radioactive materials
NPL	National Priorities List
NRC	National Research Council

NRCS	Natural Resources Conservation Service
NURE	National Uranium Resource Evaluation
OECD	Organisation for Economic Co-Operation and Development
OR	odds ratio
OSHA	Occupational Safety and Health Administration
P_2O_5	phosphorus pentoxide
PAl	peraluminous magmas
Pb	lead
pCi/L	picocuries per liter (1×10^{-12} Ci/L)
PEL	permissible exposure limit
PNEC	predicted no-effect concentration
ppm	parts per million
PR	Prognosticated Resources
Ra	radium
RAR	Reasonably Assured Resources
RCRA	Resource Conservation and Recovery Act
REE	rare earth elements
REL	recommended exposure limit
rem	roentgen equivalent in man (1 rem = 0.01 Sievert)
Rn	radon
RR	relative risk
SDWA	Safe Drinking Water Act
SMR	standardized mortality ratio
SR	Speculative Resources
Sv	Sievert
Ta	tantalum
TAG	technical assistance grant
TENORM	technologically enhanced naturally occurring radioactive materials
Th	thorium
ThO_2	thorianite (thorium oxide)
Ti	titanium
tU	metric tonnes uranium
U	uranium
USDOE	U.S. Department of Energy
USDOT	U.S. Department of Transportation
USEIA	U.S. Energy Information Administration

USEPA	U.S. Environmental Protection Agency
USNRC	U.S. Nuclear Regulatory Commission
U_3O_8	triuranium octoxide, one form of yellowcake
UMTRCA	Uranium Mill Tailings Radiation Control Act
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UO_2	uranium dioxide
VA DEQ	Virginia Department of Environmental Quality
VA DGIF	Virginia Department of Game and Inland Fisheries
VA DMME	Virginia Department of Mining, Minerals and Energy
VCCER	Virginia Center for Coal and Energy Research
VDH	Virginia Department of Health
VUI	Virginia Uranium, Inc.
WHO	World Health Organization
WL	working level
WLM	working level month
WNA	World Nuclear Association
YPLL	years of potential life lost
Zr	zirconium